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Application Of Dynamic Techno-Economic Assessment: A Case Study In Rare Earth Element Extraction

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Application of Dynamic Techno-Economic Assessment: A Case Study in Rare Earth Element Extraction

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ABSTRACT

Rare earth elements are critical materials for many technologies driving the energy industry forward. However, there is increasingly low security and lack of sustainability of current supplies. New sources and processing methods are needed and are being intensely investigated among U.S. energy leaders such as rare earth extraction from lignite coal in North Dakota. A critical need is to confirm the technological and economic viability of these approaches, aspects which are inherently interconnected, would benefit from a dynamic approach. The current approach is Techno-Economic Assessments (TEAs). TEAs evaluate the economics of the process and commercialization of the technology for viability before substantial investment is made. Standard TEAs are high-effort endeavors, and most often performed in a spreadsheet format, with hundreds to thousands of built-in equations and assumptions. Due to these features, standard TEAs have a high potential for errors and can be difficult to effectively communicate with stakeholders. Standard TEAs also do not allow for evaluation of critical dynamic variables or feedback loops within the system. TEAs drive decision making; errors in them may either limit the potential of processes if the economic results are understated or may mislead investors if the economic potential is overstated. An alternative methodology is system dynamics (SD) modeling. SD models are developed and presented in a clear visual format with explicit assumptions. SD models also readily incorporate and utilize dynamic variables. Based on these factors, SD is proposed to be a more comprehensive, less error prone, and more accessible approach than the current, standard approach to TEAs. This research effort utilized systematic literature review and application of SD modeling to an existing rare earth TEA to evaluate if the benefits of SD could enhance the outcome of a standard TEA. The findings suggest that a generic TEA structure can be applied to real projects resulting in the discovery and correction of errors and inclusion of more realistic aspects of the project resulting in more likely outcomes. In the cases analyzed, the corrections and improvements result in substantial increase in the economic potential of the process.

Contents

CHAPTER 1

1 INTRODUCTION

1.1 Overview and Purpose of this Work

1.1.1 Importance of Rare Earth Elements

Rare earth elements (REE) have come to be a necessary component to support various technologies in the clean energy, electronics, and defense industries (Nakano, 2021). This is accompanied by a substantial lack of ubiquity in the sources of such critical material. China is the dominant supplier of mined rare earth elements and the subsequent components utilized in many technologies (Tsafos, 2022). In addition to the lack of differentiation in the supply, there are also concerns about the environmental impact of the processes used in the Chinese specific rare earth processes (Wang et al., 2017). This has resulted in an aggressive search for alternative sources of rare earth elements as well as alternative technologies to process the raw material into usable materials without the same environmental impacts (Tsafos, 2022). The emerging supply driver is growth in the demand industries, especially renewable energy & electric vehicles; mined sources won't be able to keep up by ~2035 (Nakano, 2021). This problem may impact many aspects of the energy industry and its transition to a more sustainable future.

With the lack of sustainable sources, tenuous supply chains, and increasingly critical demand for rare earth elements, novel processes on alternative resources are an important part of the future of rare earth elements. Such processes must be vetted for their technological and economic capability to ensure they will be able to support the future needs of the rare earth industry.

1.1.2 Techno-Economic Assessments

Techno-Economic Assessments (TEAs) are tools used to evaluate the technical and financial viability of novel processes or changes to processes (Burk, 2018). It is these kinds of novel processes, when implemented at a commercial scale, that drive progress, but the technical and economic aspects of the process must make sense. This need for accurate results from TEAs underscores their importance but also their challenge. The number of factors that must be considered and internally consistent are large and the resulting products of an effort to build a TEA are often complex and yet must be validated and understood by many parties. This work strives to evaluate an approach to techno-economic assessment using system dynamics. The goal is to develop and document a method that is easier to understand, less mistake-prone than standard techniques, and more accurate than TEAs developed using spreadsheets. As a case study, this approach is applied to an existing set of TEAs for a process to extract rare earth elements from lignite coal. The structure of this work explores the necessary background areas and then combines elements of the background into a single approach. Specifically, the need for TEAs is explored, the background of system dynamics is introduced, and the challenges with spreadsheets are reviewed. The best practices for spreadsheet modeling and system dynamic modeling are then discussed as a backdrop for evaluating spreadsheets and building the models used in this research and finally, the background on rare earth elements sets the stage for the case study used in this work. A literature review of TEA and rare earth elements, as well as TEA and system dynamics, identifies the start of the art in those areas and provides a set of expectations for a rare earth element related TEA and a starting point for system dynamic modeling of TEA. Elements of system dynamics that are not included in a TEA but may be relevant to the types of results seen in the review of TEAs are then identified. The review of the TEA then allows for the development of a set of the common components of a TEA in a system dynamics modeling format. The areas of past system dynamics work that may be relevant to TEAs are then evaluated as they pertain to TEAs. Using the methods of the system dynamics modeling approach as applied to TEAs, an error identification effort is conducted on a spreadsheet-based TEA of the rare earth extraction process. The additional SD elements relevant to TEAs and the generic TEA components in SD are applied to the most recent TEA for the rare earth extraction process and the results between the spreadsheet version and the dynamic version are analyzed. A visual depiction of how these topics are structured within the chapter format in this work is shown below. There are additional chapters beyond what is shown but the key flow of the work is included.

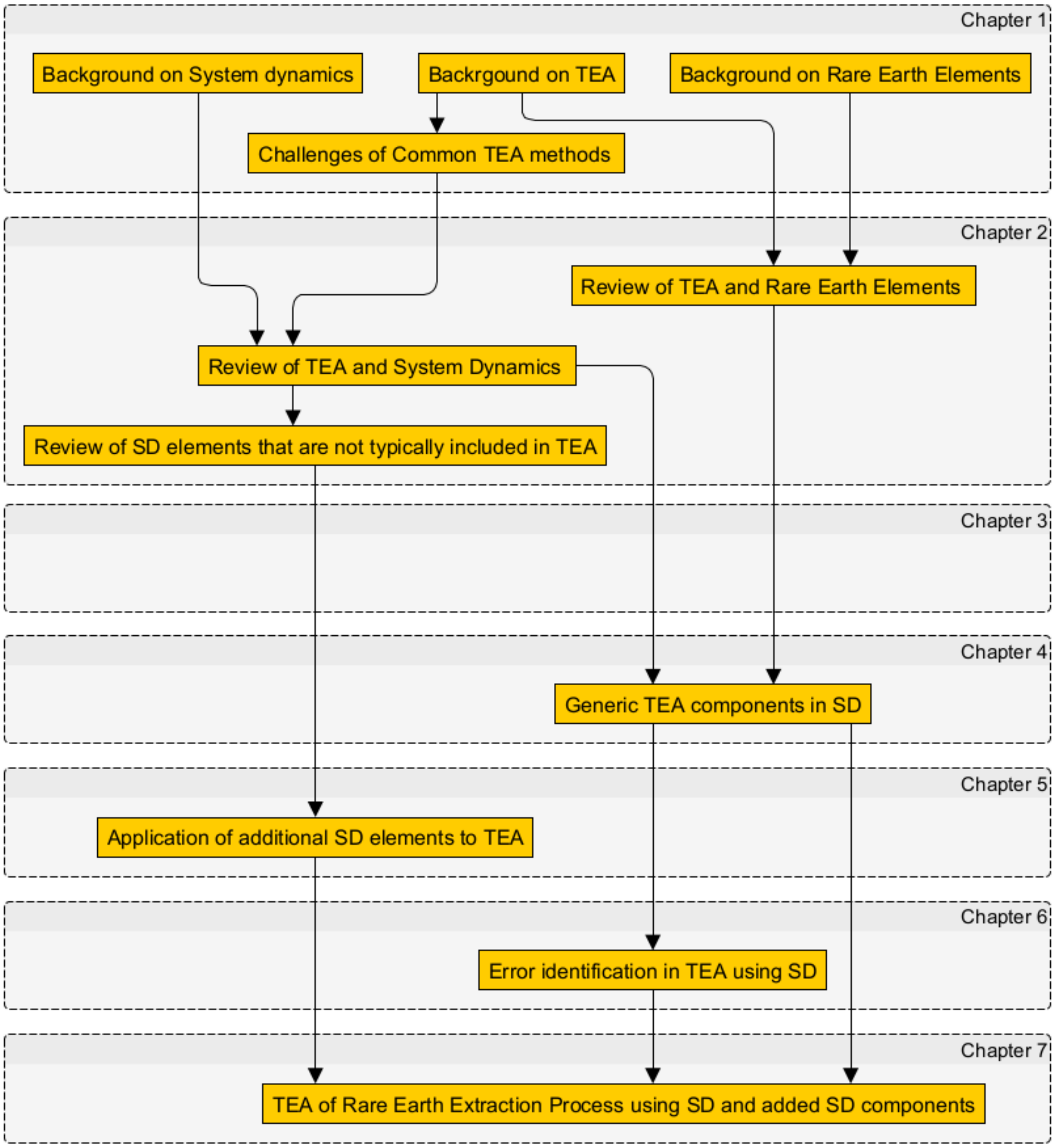

Figure 1 Research Overview Diagram

1.2 Application of Techno-Economic Assessment

New technology development requires a match between the technological capability of the process and the economic performance, such as positive net present values or acceptable returns on investment, in order to make long term impacts in its area sustainable. One method to evaluate the these aspects is a Techno-Economic Assessment (TEA) which can be used both for guiding research and development objectives to support the technological goal and to show the likely returns from an investment in said technology (Ismail & Abidin, 2021). As stated in Das et al. (Das et al., 2018) TEA combine the process model, economics of the project, and consider the uncertainty inherent in the technology or economics. They continue to describe the outputs of TEA such as identification of equipment and material needs, cash flow, and expectations of scaling and process improvements. They then affirm the fact that these kinds of estimates and extrapolations result in uncertainty that must be represented appropriately via methods such as sensitivity analysis (Das et al., 2018).

The TEA approach combines the cost elements of a process or process change by considering the capital costs and operating costs, at both a direct and indirect level, and the revenues from selling products or reductions in costs to evaluate the economic performance via a variety of commonly used metrics (Deng et al., 2021).

1.3 Challenges of Common Tools and Approaches and Relation to Dynamic Modeling

A common tool for the development of TEAs are spreadsheet tools due to their flexibility as well as ubiquity in modern business (Humbird, 2021). A review of the challenges identified in the literature as well as the best practices to address those challenges has been conducted. This effort is intended to help discover where errors may be incorporated into TEAs as well as what processes should be followed to minimize this effort. Additionally, the best practices of spreadsheets may be compared with and applied to system dynamics modeling best practices to improve models of both varieties.

The research surrounding spreadsheets has been collated by the European Spreadsheet Risks Interest Group (EuSpRiG). EuSpRiG's website was reviewed for research that aligns with the types of spreadsheet modeling done for TEAs. Their collection contains over 150 papers related to spreadsheets, best practices, and examples of challenged models and modeling efforts. Research regarding system dynamics best practices was conducted by looking at the System Dynamics Review for search terms containing "best practices". The results were then reviewed by title to determine their applicability.

1.3.1 Applicability of Spreadsheet Research to Technical Models

Articles were screened based on their relevance to the types of models that are used in TEAs. Articles related specific to fraud and lack of archives were eliminated as they are not specifically relevant tot TEA efforts. Areas of challenges that were evaluated and determined to be related were those related to human error, overconfidence, and interpretation. Articles associated with best practices, spreadsheet testing, design principles, and documentation were also included and reviewed. Of the roughly 150 articles available, 35 articles were determined to be relevant specifically to the TEA process in the above categories. For the system dynamics articles, the screening by title allowed for sufficient screening for this analysis. The existing work on spreadsheet analysis has two aspects that are relevant to this work. First is that challenges that are seen within complex spreadsheets. Second is the methods that have been developed to make spreadsheets less error prone and more useful.

1.3.1.1 Spreadsheet Challenges

Errors in spreadsheets have been documented to cause costly mistakes, as noted by Bewig (Bewig, 2013).

Table 1 Examples of Errors in Spreadsheets (Bewig, 2013)

Error	Cost	Result	Industry
Cut and paste	$24 million	Underbid on contract	Electrical Utilities
Missing minus sign	$2.6 billion	Overstate earnings	Financial
Falsely linked sheets	$700 million	Allowed for fraud	Financial
Untested macro	Unknown	Delayed product release	Pharmaceutical

It has been found that the length of a spreadsheet is the best indicator for the number of errors in that spreadsheet, with the research showing it is about 2% of all cells with formulas that have errors (Panko & Ordway, 2008). This is corroborated by cognitive research into the rate at which humans make errors. Cognitive research has shown that human error rates tend to be on the order of 2% to 5% when working on complex cognitive tasks (Panko, 2008a). Certain studies have shown that about 86% of spreadsheets that were noted as substantial, implying many errors of a more common but less impactful nature may have excited (Panko, 2008a). A compilation of studies regarding the cell error rate is shown below, including cell error rate (CER):

Table 2 - Studies and Results on Error Rates in Spreadsheets (Panko, 2008a)

Study	**Year**	**Sample**	**Subjects**	**Spreadsheets**	**% w Errors**	**Cell Error Rate (CER)**

Brown & Gould	1987	ED	9	27	63%	NR
Olson & Nilsen (1,2)	1987-1988	ED	14	14	NA	21%
Lerch (1,2)	1988	ED	21	21	NA	9.3%
Hassinen (2) on paper	1988	Ugrad	92	355	55%	4.3%
Hassinen (2) online	1988	Ugrad	10	48	48%	NR
Janvrin & Morrison (3) Study 1, alone	1996	Ugrad	78	61	NR	7% to 10%
Janvrin & Morrison (3) Study 1, dyads	1996	Ugrad	88	44	NR	8%
Janvrin & Morrison (3) Study 2, alone	1996	Ugrad	88	88	NR	8% to 17%
Kreie (post test)	1997		73	73	42%	2.5%
Teo & Tan (4)	1997	Ugrad	168	168	42%	2.1%
Panko & Halverson, alone	1997	Ugrad	42	42	79%	5.6%
Panko & Halverson, dyads	1997	Ugrad	46	23	78%	3.8%
Panko & Halverson, tetrads	1997	Ugrad	44	11	64%	1.9%
Panko & Sprague (4)	1999	Ugrad	102	102	35%	2.2%
Panko & Sprague (4,5)	1999	MBA (NE)	26	26	35%	2.1%
Panko & Sprague (4,6)	1999	MBA (ED)	17	17	24%	1.1%
Panko & Halverson, monads	2000	Ugrad	35	35	86%	4.6%
Panko & Halverson, triads	2000	Ugrad	45	15	27%	1.0%
Total Sample			998	1170	51% (7)	
NR = not reported						
ED = experienced developer						
NE = not very experienced with development at work						
Ugrad = undergraduate students						
(1) Measured errors before subject had a chance to correct them						
(2) Only measured error rate in formula cells						
(3) Only measured error rate in cells linking spreadsheets						
(4) Wall Task designed to be relatively simple and free of domain knowledge requirements						
(5) MBA students with little or no development experience						

(6) MBA students with considerable development experience						
(7) Weighted average						

Errors in spreadsheets can be due to many causes. Poor practices can not be tied directly to these errors but poor practices can be tied to common issues such as hard coded numbers in formulas but quantitative errors are rare and impactful errors are even rarer (Powell et al., 2009).

1.3.1.1.1 Types of Errors

Panko describes the types of errors that are common in spreadsheets (Panko, 2008a). He first describes the two broad categories of quantitative errors and qualitative errors. Quantitative errors result in a value that is wrong somewhere in the sheet. He notes that one type of quantitative error is mechanical in nature, such as mistyping a number or incorrect cell references in a cell or formula. Another quantitative error is that of an error in logic where an incorrect formula is used for a calculation. And finally, errors in the omission of aspects of the model that are needed to solve the problem are the final quantitative error type. The concern with qualitative errors is less with the immediate wrong number somewhere but more in regard to issues that may happen later due to misuse of the model. These errors can occur due to poor design where users may enter data incorrectly, interpret results incorrectly, or change an input but due to an unknown hardwired number receives an incorrect output.

1.3.1.1.2 Overconfidence

Another contributing factor that has been explored is overconfidence. As Panko Et.al (Panko, 2008b) discuss, it is a common human trait that is also seen in spreadsheet development. They show via one experiment that spreadsheet developers report the probability of an error in their work at 18% while the actual value was 86%. A second experiment showed that providing warnings and feedback to the developers caused 3 times the number of developers to make a correct spreadsheet. They report that this still leaves the likelihood of error at a high level that is potentially unacceptable for spreadsheets to be trusted without validation. An additional finding that was of interest was that developers reported that other developers likely would have a lower rate of errors than themselves implying that they are not only overconfident in themselves but also in others (Panko, 2008b).

1.3.1.1.3 Review Time/Effort

The process of auditing and revenging spreadsheets for errors has also been researched. One such approach noted that it is a multi-step process of a low level review looking at the model formulas and then a high-level review of the overall function and how the model performance can take between 25 and hundreds of hours (Croll, 2007). It is at this stage that a sensitivity analysis on the spreadsheet can be performed which may identify other areas that are not logically correct or need to be better understood which requires the choice of several key variables and manually change them to observe the output from the spreadsheet (Croll, 2007).

1.3.1.1.4 Differences Across Sectors

In a study of various sectors which utilize spreadsheets, it was determined that there is not much difference between sectors in terms of the frequency of spreadsheet errors and the perception about the impact from errors in spreadsheets leading to losses and bad decisions (Caulkins & Morrison, 2007).

1.3.1.2 Way to Reduce Spreadsheet Errors

1.3.2.2.1 Planning

Conditional formatting of cells allows for putting an expected range of the outputs of the spreadsheet such that if the output is outside of that range the formatting changes and is easily identified as an area that needs to be investigated (Bewig, 2013). Planning how the sheets will be maintained throughout their lifecycle can help prevent errors from being integrated over time and use of the documents (Grossman, 2002). Working with the uses of the sheet and its products can prevent errors from being incorporated based on a misperception of the use or the logic of the spreadsheet (Bewig, 2013).

1.3.2.2.2 Testing

Testing is a commonly discussed method to improve spreadsheet errors in the literature. The types of tests are varied in focus area and scope. Before the modeling even begins it is recommended that the requirements and specifications be tested for reasonableness and logic which may prevent future errors from occurring (Panko, 2007). Unit testing of calculations can also find errors within a spreadsheet although it is one of the more detailed tests which takes the most time to conduct (Panko, 2007; Pryor, 2008). Eyeball testing, or reasonableness testing is another type of test that is done on the result of the spreadsheet to see if the results fit within the expectations based on the known inputs to the sheet (Panko, 2007, 2008a; Pryor, 2008). An additional test is a cell by cell review of the sheet looking for errors. There also exist complex testing methodologies that have been born out of the processes developed for formal software testing (Rothermel et al., 2001). There are some concerns around testing as it may be used in a sampling approach where only portions of the model are tested (Mittermeir et al., 2008).

1.3.2.2.3 Documentation and Commenting

Various forms of documentation and commenting approaches for spreadsheets have been investigated and are summarized below:

- Dependency graphs – One method used to capture how a spreadsheet is structured and works is a dependency graph which shows how various elements are used and what uses them as the sheet is either planned or built (Bewig, 2013).
- Precedence tracing - Features in the spreadsheet software have been developed to allow for understanding the connections in a cell such as the trace dependence and precedence tools which show the connections between the target cell and the cells which use it and which it uses to get its result (Butler, 2006; Izza, 2022).
- Comments adding – Adding comments to spreadsheets also helps to reduce errors by making the logic of a portion of the sheet clear to future users (Payette,

2008). This process can be simple on the fly comments with cells (Butler, 2006) or a more formal documentation process documenting the data, changes, the purpose and method of calculations, who created it and when, and how it has changed over time (Payette, 2008).

1.3.2.2.4 Readability

Raffensperger (Raffensperger, 2008) has identified a new style of a spreadsheet that makes the more readable. This style is distinct from programming style due to the differences in spreadsheets and computer programs. He first recommends that readers expect sheets to be read from the left to the right and from the top to the bottom. He also emphasizes the need to be concise, especially in terms of using multiple sheets unnecessarily as it is harder to follow. Simplified formulas are also part of the recommendation for easier readability. Additionally, he recommends using formatting to guide the attention of the user rather than just as a way to make the sheet look nicer. Finally, he encourages the spreadsheet to expose data and labeling rather than hiding it, including hiding cells unnecessarily (Raffensperger, 2008).

1.3.1.3 System Dynamics Approach to Model Building

Research on the best practices for system dynamics modeling can be categorized into several areas across the development process of modeling. Different approaches have been developed for the modeling process, but they all follow a common general cadence. The approach that will be used as a framework for evaluating the literature will be that of Randers (Randers, 1980). He identified the following stages of the modeling process:

- Conceptualization
- Formulation
- Testing
- Implementation

Other approaches have been developed by different practitioners but in general, they can fit within this same framework as shown by Martinez-Moyano et al.:

Table 3 Stages of System Dynamics Modeling Process (Martinez-Moyano & Richardson, 2013)

Randers (1980, p. 119)	Richardson and Pugh (1981, p. 16)	Sterman (2000, p. 86)	This study
Conceptualization	Problem Identification and Definition	Problem Articulation (Boundary Selection)	Problem Identification and Definition
	System Conceptualization	Formulation of Dynamic Hypothesis	System Conceptualization
Formulation	Model Formulation	Formulation of a Simulation Model	Model Formulation
Testing	Analysis of Model Behavior	Testing	Model Testing and Evaluation
	Model Evaluation	Policy Design and Evaluation	
Implementation	Policy Analysis		Model Use, Implementation, and Dissemination
	Model Use or Implementation		
			Design of Learning Strategy/Infrastructure

1.3.1.3.1 Conceptualization

Conceptualization of the model is noted as a critical step of the process, specifically regarding the definition of the problem and the purpose of the modeling effort (Martinez-Moyano & Richardson, 2013). This is expanded on to include a variety of actions, much of which revolve around understanding the problem and behavior in more detail. Some of these actions are to thoroughly define the identified problem, make clear the purpose of the work being done, develop the reference modes of past behavior or concerns for future behavior, and gather key variables and causes of issues or concerns (Martinez-Moyano & Richardson, 2013). It has been noted as well that the order of these actions is an important factor in the successful development of a model and that getting the data and historical context is needed before problem definition and diagramming (Homer, 2019). This list is not exhaustive but sets the stage for a successful conceptualization which is then described as identifying key building blocks of the system and understanding what are the accumulations that may exist in the system (Martinez-Moyano & Richardson, 2013). Developing the purpose and scope of the model alongside stakeholders allows for a better conceptualization of the model via data analysis, interviews, and workshops which leads to the collected knowledge maps which can be represented diagrammatically depending on the nature of the problem (Elsawah et al., 2017). Additional elements that are relevant to a good model conceptualization are summarized as the context, reference modes, model purpose, system boundary, and feedback structure (Richardson & Pugh, 1997). These model conceptualization best practices create the beginning framework for a successful model and support the next steps of the modeling process.

1.3.1.3.2 Formulation

The purpose of the mode formulation stage is to develop a quantitative model based on the information and qualitative diagrams derived from the conceptualization phase (Elsawah et al., 2017). As this quantification process is performed it is recommended that models start simple and incrementally increase in complexity as needed while maintaining consistent units and dimensional consistency in equations that are clear and with parameters that have a meaning in the real world (Martinez-Moyano & Richardson, 2013). Logical relationships and realism in formulations are essential in formulating the model based on the hypothesis developed in the conceptualization phase (Homer, 2019). The formulation effort can be aided by using existing models as either a component of the model or as guidance for the formulation (Elsawah et al., 2017). At the end of this stage, a simulating model will be producing results that can be compared with data and collected information.

1.3.1.3.3 Testing

The testing phase can have several parts. First is the comparison of the model outputs with the data and where there are differences, find additional information that helps to identify parameter changes, equation changes, or missing components to the model (Homer, 2019). In addition to evaluating the model results against historical behavior or reference modes where historical behavior is not available, the model should respond in logical ways to extreme values or shocks to the system (Martinez-Moyano & Richardson, 2013). Using statistical methods to compare the historical or reference behavior with the model is recommended and a range of methods have been developed (Elsawah et al., 2017). Second is the sensitivity of the model to various parameters or policies which may require model changes as the results of the sensitivity analysis are compared with the data and stakeholders (Homer, 2019). This process can be continually conducted from the beginning of the formulation process to limit the need for large revisions later in the modeling project (Elsawah et al., 2017). Model testing ensures that the model is in agreement with data and is robust.

1.3.1.3.4 Implementation

The reason for developing a model is for it to be used to address the issues identified in the conceptualization phase. One approach is to evaluate different scenarios with the model along side users or by users themselves to provide a rapid assessment and comparison of those scenarios (Elsawah et al., 2017). Another approach is to use model-based stories that illustrate the problems the model was built to address which makes sure the effort addresses those problems and communities the insights effectively (Martinez-Moyano & Richardson, 2013). These approaches ensure that the model has met the identified need and can be used to assist in problem solving.

1.3.2 Analysis of Best Practices

Both system dynamics and spreadsheet research provide best practices that can be evaluated relative to each other and improve the outcome of both modeling methods.

1.3.2.1 Commonalities for Spreadsheets and System Dynamic Best Practices

For both modeling methods, there is a strong emphasis on planning and conceptualizing the problem that is being addressed with the model. With a clear conceptualization of the problem, errors in the omission of aspects of the problem will prevent an accurate model from being developed. In the case of TEAs, it is important for a clear scope of the model to be developed but also to be sure to include aspects of the problem that can affect the economic and technical outcomes.

Testing is also common to both best practice recommendations. Extreme value testing and reasonableness checks are common in both approaches. They can be semi-automated by putting alerts into the models that make it known when parameters are outside of expected ranges. Another form of testing is unit checking; this process is very automated in system dynamics but can be done in excel as well to ensure that calculations are dimensionally correct.

Attention to readability in spreadsheets is shown to improve the accuracy and concern in the formulation phase of the model for readability is also important in dynamic modeling. The ability for others to understand what the model is doing easily is a great benefit to both methodologies and can prevent errors from being introduced due to misunderstandings.

1.3.2.4 How Might the Spreadsheet Insights Help System Dynamics

Some additional recommendations from the spreadsheet world that could benefit the best practices of the system dynamics modeling approach have to do with documentation. Documentation via comments or clear descriptions of the approach and the method are known in the spreadsheet research to reduce errors, especially for future users. These same approaches can pay dividends when it comes to dynamic models. Commenting capabilities exist in the software to describe the intent or other features behind each variable and written documentation of the model purpose, methodology, and use cases can make future uses understand and be able to apply the model without fear of mistakes being introduced.

1.3.3.5 Gap in Spreadsheet Research

Research on technical models in spreadsheet software is a gap that is observed when reviewing the spreadsheet literature. There is much focus on financial spreadsheets but very minimal focus on how spreadsheets are used in the technical and engineering fields and how in any way that may lead to different outcomes from the research.

1.4 A Case of Rare Earth Element Extraction

1.4.2 Rare Earth Elements and Extraction from Lignite

Rare earths can be viewed from the perspective of their uses and in technology and energy applications as that is a strong part of the motivation for alternative sources and recycling (Lucas et al., 2015). One alternative source that has been investigated is coal and the byproduct of coal which is a large source of rare earth elements and initial investigations into extraction and recovery from such feedstock have been conducted (Zhang et al., 2015). Investigations into such coals have shown that in many cases the rare earths are in potions of the coal that are suitable for extractive methods of separation from the coal (Finkelman et al., 2018). Such extractive methods have been explored in detail in a broad set of research (Stevenson & Nervik, 1961). This potential has inspired a variety rare earth related research efforts focusing on methods of extraction and separation for novel sources, especially coals (NETL, 2019)

1.4.2.1 North Dakota Lignite

As explored by Laudal, a process has been developed that is effective at rare earth extraction from lignite in a manner that minimizes waste products (Laudal, 2017). As he explains this process utilizes the lignite deposits of North Dakota, which is beneficial both from the degree of lignite availability and of the capability of the North Dakota economy which is capable of mining lignite and using coal products. Several mines in North Dakota have provided samples that have substantial REE concentrations above 300 ppm in certain parts of the seam (Mann, 2021). These results have been confirmed by the North Dakota geological survey (Kruger et al., 2017; Moxness et al., 2021; Murphy et al., 2018). Additionally, laboratory data on the mineral composition of the coal before and after the leach testing has been reported and provides evidence of the coal being free of many impurities after processing (Mann, 2021).

1.4.2.2 REE and Byproducts Processing and Markets

The process from rare earth ore to market has been outlined at a high level by Lucas et al. both for ore and oxide. It is assumed that the market is for rare earths as raw materials rather than as final products.

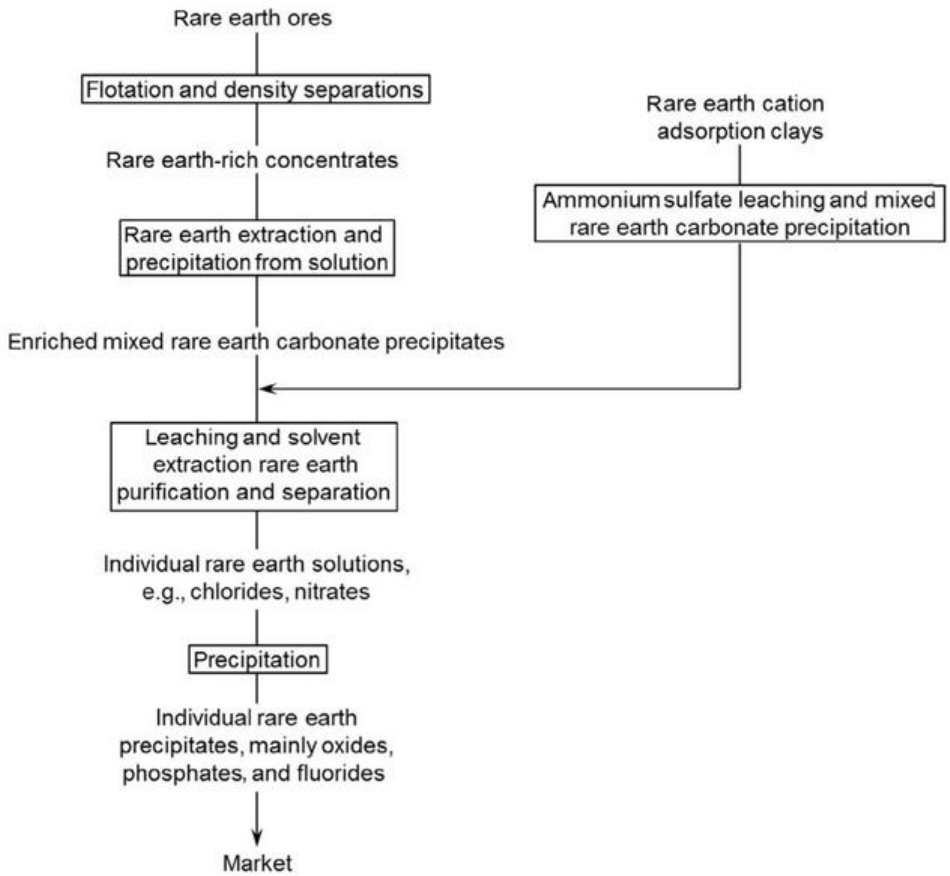

Figure 2 Rare earth processing (Lucas et al., 2015).

Historical information on the pricing and size of the REE market is very useful when considering the current state and future of the market. This kind of information can help validate assumptions and ensure that any considerations regarding where the market is going have their roots in reality (Fernandez, 2017).

1.4.2.3 Coal Options

As processed coal is a byproduct of the REE, process alternative uses of that coal besides power generation may bring other value streams to the process. There is a strong desire for finding alternative uses of domestic coal for alternative products or improving the quality of the coal for combustion. Improving the quality of the coal can increase the value of the coal as it can help some electricity generation processes increase their efficiency, although this is not true for all systems as some may not see the benefit due to other systems parameters (Satyamurty, 2007). In addition, to use for combustion for energy generation, an improved coal product may support the larger coal-to-product markets such as outlined by Atkins including(Atkins, 2019):

- Liquid fuels and chemicals
- Carbon fiber, activated carbon, graphite, graphene, construction products
- Fertilizers
- Sensor applications

The range of potential products is encouraging as a strong range of markets for one of the main products of the rare earth extraction process, including many that may support other forms of the energy transition as is the case for increased rare earth production (Serpell et al., 2021). The U.S. federal government has outlined the goal of a more domestically centered REE supply due to the critical nature of the products they are used, the importance of REE for the U.S., and the challenges with supply (EERE, 2020).

1.4.2.4 TEA Efforts on Rare Earth Element Extraction in North Dakota

With the confirmation of rare earth element concentration in North Dakota Lignite and the development and laboratory testing of a process for extraction, a series of TEAs have been conducted which intend to investigate this process for commercial viability. The TEAs have been created in spreadsheet software and results of the early versions of these TEAs have been reported (Mann, 2021). These will form the basis for the analysis of this work.

1.5 Application of the Term "Dynamic TEA"

Elements of TEAs have been conducted with a system dynamics modeling approach as is examined in Chapter 2, but as noted by Deng et al. there are market dynamics that are needed to be incorporated into what was defined as a "dynamic TEA" (Deng et al., 2021). This work intendeds to expand that definition to include dynamics in many areas of a TEA, including the market dynamics such that the term "dynamic TEA" can encompass the broad range of elements in a TEA that may change over time.

1.6 Background on System Dynamics

The nature of TEA is one of the interconnected elements affecting the outcomes of the effort which can be well supported by a dynamic modeling approach such as system dynamics or agent-based modeling/hybrid modeling (Linnéusson, 2009). System dynamics was developed by Jay Forrester starting in the 1950s as a means to bring science and engineering into the management of corporations (*Origin of System Dynamics*, n.d.). The approach can be used to help design better policies and shape approaches to interconnected systems in a way that enhances understanding and improves outcomes (J. D. Sterman, 2000). This includes applications to novel technologies in the energy industry (Tomomewo, 2021).

1.7 Theoretical Framework, Hypothesis, and Research Questions

Given the importance of TEAs for novel processes, as is exemplified by the extraction of domestic REEs from North Dakota lignite, and the challenges with spreadsheets as one of the major approaches, this work evaluates a variety of gaps in the research on how to improve the approach for TEA development via the application of SD modeling and to the TEA process.

TEAs built using the system dynamics methodology are likely to include more relevant elements, built from common components applied to the specific process, and contain fewer errors than a standard spreadsheet-based TEA. To evaluate this hypothesis, the following research questions are evaluated.

1.7.1 Research Question 1

How can common components of TEA be represented in SD tools such that dynamic TEAs are not one-off efforts?

TEAs take time and effort to develop and if a generic approach can support the development of a specific application, then improved TEAs can be built with less effort.

1.7.2 Research Question 2

What feedback loops or processes are not typically considered in TEA that can be incorporated with SD?

With the reviews of literature using TEAs, we intended to show the elements of TEA feedback processes that are not present in standard TEAs.

1.7.3 Research Question 3

How does system dynamics modeling change error identification in TEAs?

TEAs are important documents to drive decision making and errors in them may either limit the potential of processes if the economic results are understated or may mislead investors if the economic potential is overstated.

1.7.4 Research Question 4

How does the augmented sensitivity analysis capability of SD change the process or outcome of TEAs?

As TEAs are inherently uncertain, the ability to robustly evaluate parameters may improve the outcome over the standard methods.

1.8 Research Aim, Structure, and Significance

System dynamics and hybrid modeling approaches have been used in business, technology, management, healthcare, and policy for complex system analysis within diverse areas including with TEA in various cases as are reviewed in this analysis (Jokar & Mokhtar, 2018). This research intends to understand how TEA has been used concerning rare earth element technologies and how dynamic modeling has been applied to TEA in other areas to assess the application of an integrated TEA using dynamic modeling methods. This provides an understanding of what aspects of TEAs are commonly used by rare earth projects such that a dynamic TEA can be sure to incorporate the necessary elements. Also, past work on making elements of a TEA in the system dynamics approach provides a basis for what has worked and what areas could be improved.

Research Structure

Chapter 1 provides an introduction to TEAs, and the importance of TEAs to new technology development. Additional information regarding the challenges of spreadsheets which are a common tool for the development of TEAs is explored. A brief background on system dynamics and a more detailed overview of rare earth elements in general and the specifics of the UND extraction process are provided.

Chapter 2 explores the range of implementation of TEAs for technology surrounding rare earth elements. These intendeds to understand what aspects of a TEA are important to rare earth projects to support the development of the dynamic TEA for rare earth elements. Next, the application of system dynamics to TEAs in literature is explored to understand how have aspects of TEAs been implemented in prior work.

Chapter 3 discusses the research methodologies used in this work. This is composed of both the work done previously in the literature of TEAs for REE technology as well as for system dynamics TEAs. TEAs examples, both REE related and non-REE related also provided data as to the structure and elements that compose a TEA. The results from several versions of the REE TEAs also are sources of data for this work. Additional work from system dynamics literature that may be applied to TEAs is also used as data for this work. Finally, data from various sources needed to parameterize the REE TEA has also been collected from the literature. Analysis methods used are comparing the results of the dynamic TEA with the known results from several spreadsheet-based TEAs for the REE extraction process.

Chapter 4 develops a generic dynamic TEA that composes the elements determined to be common in REE TEAs. This generic approach is also informed by aspects from the system dynamics literature where TEA models were used.

Chapter 5 applies the additional system dynamics elements that are relevant to TEAs to the REE TEA process. This includes the project model as informed by TEA inputs, the pricing model as applied to the REE market, and the hiring model applied to a new plant as would be used for the REE process. These models are then capable of being integrated into the TEA for the REE process.

Chapter 6 uses a form of the dynamic TEA to look at the process model and economic outputs to evaluate the spreadsheet-based TEA for errors. This is performed by replicating the key elements in the TEA and comparing the results of the spreadsheet version to the dynamic version.

Chapter 7 applies the dynamic TEA framework to the latest REE process as described by the latest spreadsheet TEA. This approach checks the spreadsheet TEA for errors and incorporates the additional system dynamics components to evaluate any differences between the spreadsheet version and the dynamic version.

Chapter 8 is a brief comparison of how the evaluated TEAs have changed over time and a reflection on the differences and if the dynamic TEA approach could have predicted the changes.

Chapter 9 discusses the results of this work, and the future directions and concludes the work in terms of its relevance.

1.9 Summary

Rare earth elements are critical materials for many technologies but are constrained in their supply in several ways (Nakano, 2021). To address those constraints a novel process has been developed at the University of North Dakota to extract and concentrate rare earth elements from lignite coal (Mann, 2021). This process has been developed via laboratory and pilot phases which have supported process modeling software and spreadsheet TEA for the commercial process (Laudal, 2017). Spreadsheets have been shown to include errors and have challenges with readability (Panko, 2008a; Raffensperger, 2008).

CHAPTER 2

2 LITERATURE REVIEW OF THE INTERSECTION OF TECHNO-ECONOMIC ASSESSMENT, REE, AND DYNAMIC MODELING

2.1 Dynamic Modeling of Techno-Economic Assessment for Rare Earth Production

The approach used in this review intends to capture what published works there are on a specific set of information, namely system dynamics/hybrid modeling and rare earth elements as they pertain to techno-economic assessments. The approach follows a combination Salim et al. and Langarudi et al. as an approach to searching and analyzing the found studies (Langarudi et al., 2021; Salim et al., 2022). A broader look at TEAs as used by similar processes to capture the commonly utilized components in a TEA and what system dynamics work has been done for these aspects that are commonly included TEAs of this nature is also considered. Specific areas of review are as follows:

- System dynamic/hybrid models and TEAs
- TEAs and rare earth elements
- System dynamics and aspects included in TEAs

2.1.1 Search Terms

The following terminology and formatting of searches encompass the range of desired topic areas. The Web of Science was used as the search tool to identify articles related to SD/hybrid models and TEAs using the search terms “Techno-economic and system dynamics”, “Techno-economic and agent based” and the search “ALL=(techno-economic) AND (ALL=("system dynamics") OR ALL =("agent based"))” with the criteria that articles must include a dynamic model as it pertains to a TEA. To understand how TEA has been used relative to rare earth elements, the search terms “Techno-economic and rare earth”, “Techno-economic and critical mineral”, “Techno-economic and magnet”, and “ALL=(techno-economic) AND (ALL=(rare earth) OR ALL =(critical minerals) OR ALL=(magnet))” was used along with the criteria that the subject of the study must include rare earth recovery.

2.1.2 Screening and Filtering

Studies from the above searches were reviewed to screen and filter out any repeats which resulted in 81 studies to screen. Following the removal of repeated articles, we screened the titles for references to rare earth elements, system dynamics modeling, agent-based modeling, dynamic modeling, and techno-economic assessments/evaluations or modeling. Upon the review of the titles, 29 studies were removed leaving 52 studies. To more fully evaluate the relevance of the studies screened by title, we reviewed the abstracts looking for approaches and results that are relevant to this review and based on this review removed an additional 8 studies, leaving 44. For the remaining articles, full texts were obtained and evaluated for relevance to this analysis which resulted in the removal of another 23 articles, leaving a total of 21 studies relevant to dynamic modeling, TEAs, and rare earth elements. The lack of literature coving both dynamic modeling, either system dynamics or hybrid modeling, and rare earth element related technologies provides an opportunity for further research to evaluate the integration of these approaches to achieve a more robust model of the feasibility of technology intended to support the critical mineral and rare earth material industries.

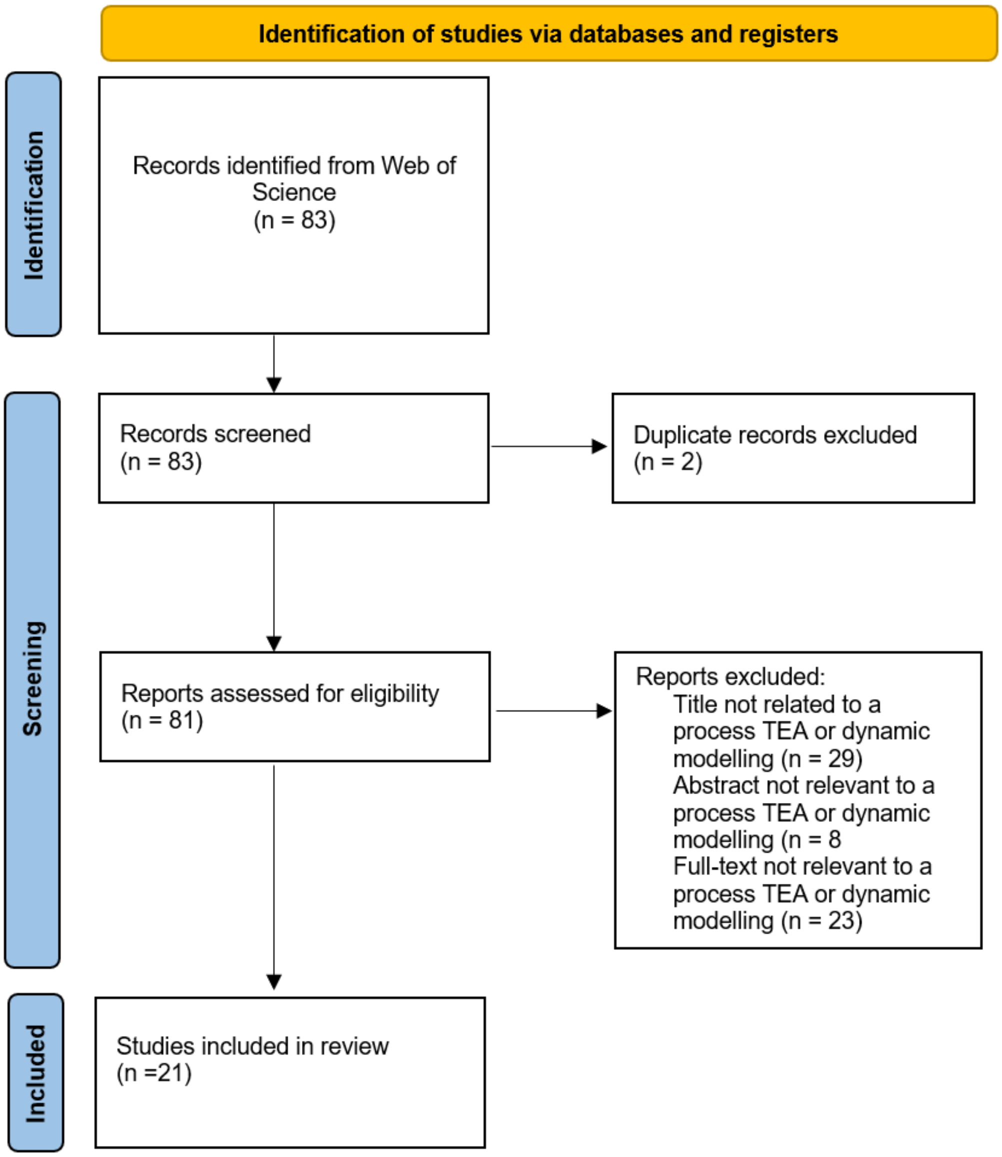

Figure 3 Literature Review PRISMA Diagram

2.1.3 Results of Literature Review for SD and REE TEAs

The included studies can be generally separated into dynamically modeled techno-economic assessments and rare earth related TEA. There is only one study with any overlap in those areas, and its focus is hard drive recycling with some form of rare earth oxide recovery (Nguyen et al., 2017).

2.1.3.1 SD and TEA

The eight studies that use system dynamics as it pertains to a TEA do so in a variety of ways. Considering the core aspects of TEAs that were observed in the standard TEA research as well as displayed in the TEAs evaluated for this study there is a span of how system dynamics has been applied to those core areas as well as extended aspects. When analyzing the approaches of various studies some common uses of SD appear across many of them. This includes some form of a process model, explorations of the capital and operating costs, an analysis of the income potential, the combination of costs and income into economic metrics, and some sensitivity testing on the resulting model.

2.1.3.1.1 Process Model in SD TEAs

Process models built in system dynamics are frequently used in SD based TEAs, especially when the process model is relativity straight forward and within the usual capabilities of system dynamics(Elizondo-Noriega et al., 2021; Fazeli et al., 2022; Laurischkat & Jandt, 2018; Proaño et al., 2020). The process model can be applied from prior research, such as by Elizondo-Noriega et. al., where a manufacturing facility model from literature was integrated with the elements of the system the authors intended to add to the process(Elizondo-Noriega et al., 2021). Alternatively, Fazeli et. al. took a very simple production process model and parametrized the simple model with assumptions from prior research of various production technologies to capture the differences between the processes at a common level (Fazeli et al., 2022).

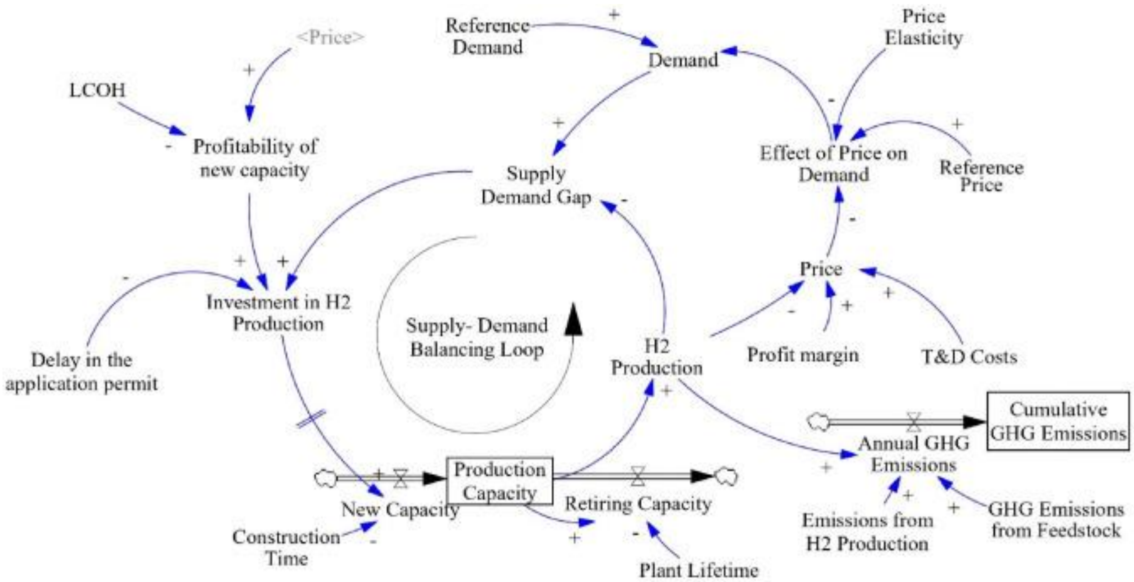

Figure 4 Simple Production Process diagram (Fazeli et al., 2022)

The use of system dynamics in the process model allows for analogies between dissimilar systems as used by Laurischkat and Jandt, where a hydraulic analogy is used to explain the model of the electrical system developed for the TEA (Laurischkat & Jandt, 2018). In some instances, the model can be a hybrid of a more standard TEA process model for elements that are more easily modeled in specialty software such as Aspen Plus and a model of other parts of the process in system dynamics (Proaño et al., 2020). Proaño et al. and Elizondo-Noriega et al. both have manufacturing processes with a common structure of material moving through a chain of process steps which shows the commons structural elements across processes, in this case from cement production and a generic manufacturing process.

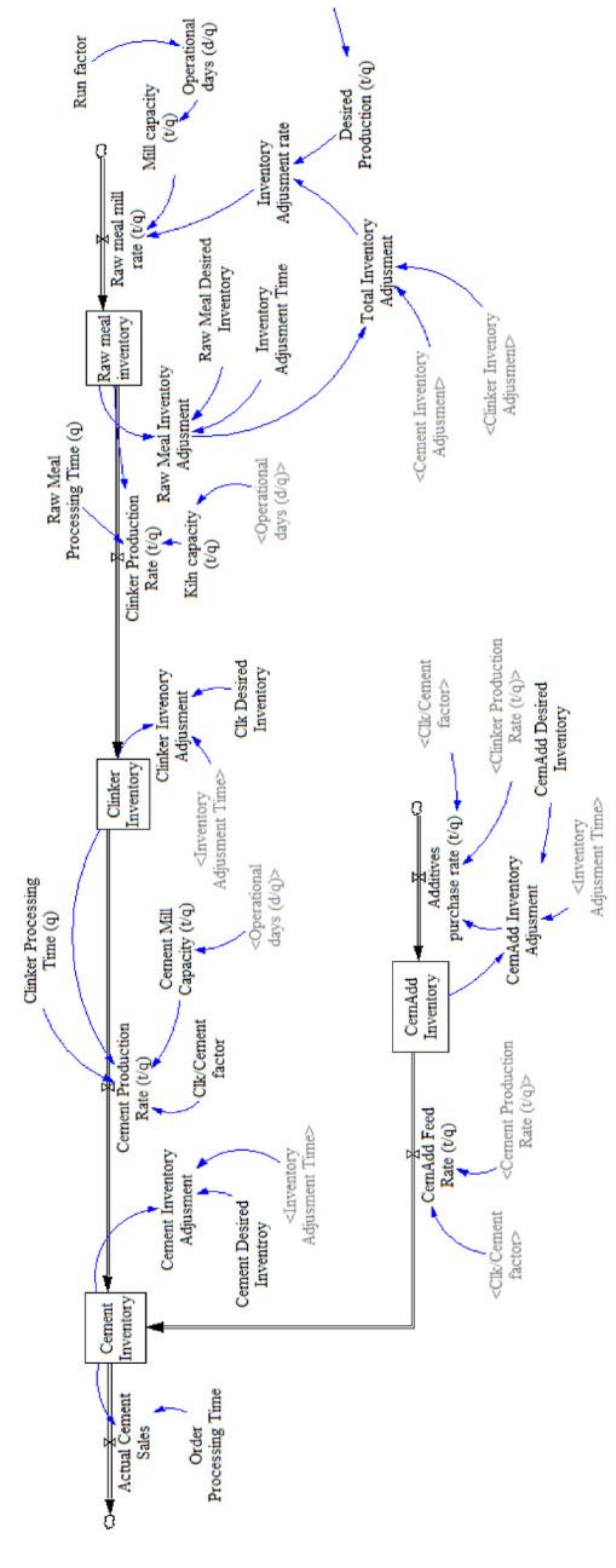

Figure 5 Process Model in System Dynamics (Proaño et al., 2020)

While the previously mentioned models intend to capture some of the physical aspects of the process, models such as those used in Fazeli et al. simply attempt to capture the production capacity of the process based on parameters regarding the time to build capacity and time for that capacity to erode which is a much higher level of consideration of the process.

2.1.3.1.2 Capital Costs in SD TEAs

In all found cases using system dynamics for the modeling methodology for a TEA, the capital costs (CAPEX) are static values based on a sizing parameter picked for the process/technology at hand. The detail of the development of the capital costs is not specified in many cases but some other tools are used to develop a capital cost estimate such as the AREA tool along with Aspen Plus (Proaño et al., 2020). In other cases, a range of capital costs from other sources are used as the capital costs in the TEA (Elizondo-Noriega et al., 2021; Fazeli et al., 2022; Laurischkat & Jandt, 2018). Fazeli et al. note how the assumptions used for capital costs are related to the nature of the technology and its level of development where mature technology capital expenses are expected to remain constant over time while more novel technologies are assumed to have a decrease in capital costs over time (Fazeli et al., 2022). Elizondo-Noriega et al. emphasize how the range of costs determined from the literature will be used as values for the sensitivity analysis of the model (Elizondo-Noriega et al., 2021). Others use a single value for capital costs for the project (Deng et al., 2021, 2021; Yu et al., 2019). Deng et al. focused on the dynamic nature of product pricing and utilized a single value of the other TEA components including the capital costs based on a standard approach to TEA (Deng et al., 2021). Similarly, Yu et al. develop capital costs based on the identified process parameters and equipment needed for the process which supports the economic side of the TEA (Yu et al., 2019).

2.1.3.1.3 Operating Costs in SD TEAs

Counter to the CAPEX approach taken, operating costs (OPEX) are much more commonly represented using an SD approach in the studies. Using an SD approach for operating cost is a logical choice when the operating cost variation is an important parameter for the overall outcome of the TEA (Elizondo-Noriega et al., 2021; Laurischkat & Jandt, 2018; Proaño et al., 2020; Yu et al., 2019). Elizondo-Noriega et al. and Proaño et al. both utilize their dynamic model of the process as drivers for the operating costs incurred as it captures when there are changes to process flows and how those changes result in operating cost changes (Elizondo-Noriega et al., 2021; Proaño et al., 2020).

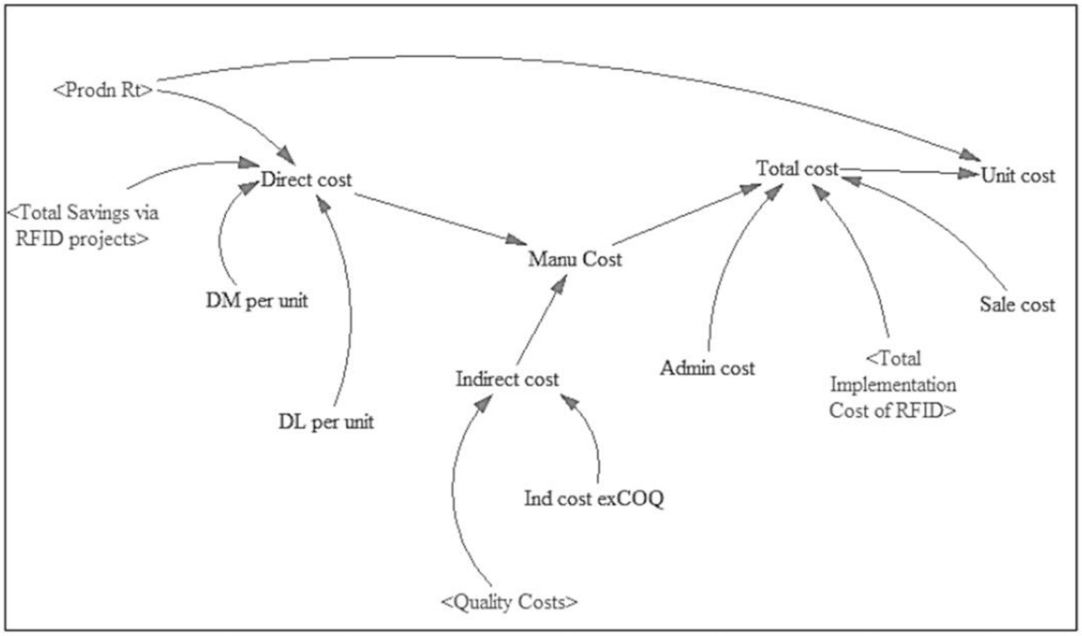

Figure 6 Operating Costs in system Dynamics (Elizondo-Noriega et al., 2021)

Similarly, Laurischkat & Jandt use their dynamic process model to determine the operating expenses where the final rates of consumption of materials drive the operating costs(Laurischkat & Jandt, 2018). This approach is not as integrated as the other mentioned studies where the dynamic model drives the operating costs dynamically, but it does still capture how the costs may change given changes to the process. Alternatively, there are cases where a more standard approach to operating costs is used for the TEA modeling, this is common when the operating costs are not derived from within the TEA but an input to the TEA (Deng et al., 2021; Fazeli et al., 2022).

2.1.3.1.5 Income in SD TEAs

Another aspect of SD based TEAs is the use of SD in the calculation of the process income. This can be as focused as the calculation of the savings due to the process or income from the products produced within an SD model (Elizondo-Noriega et al., 2021; Fazeli et al., 2022; Laurischkat & Jandt, 2018). Calculating income in that way assumes a price or cost and the rate of how much reduction there is, or product produced is what sets the final income for the process. Others can use a similar approach but have the modeling of the demand for the product or the dynamic price changes incorporated in the model of the income of the process (Deng et al., 2021; Nguyen et al., 2017; Proaño et al., 2020).

2.1.3.1.6 Economic Metrics in SD TEAs

Another aspect of SD based TEAs is the use of SD in the calculation of the process income. This can be as focused as the calculation of the savings due to the process or income from the products produced within an SD model or differences between a current solution and an alternative (Elizondo-Noriega et al., 2021; Fazeli et al., 2022; Laurischkat & Jandt, 2018). Calculating income in that way assumes a price or cost and the rate of how much product is produced and what price is what sets the final income for the process. Others can use a similar approach but have modeled the demand for the product or the dynamic price changes incorporated in the model of the income of the process (Deng et al., 2021; Nguyen et al., 2017; Proaño et al., 2020).

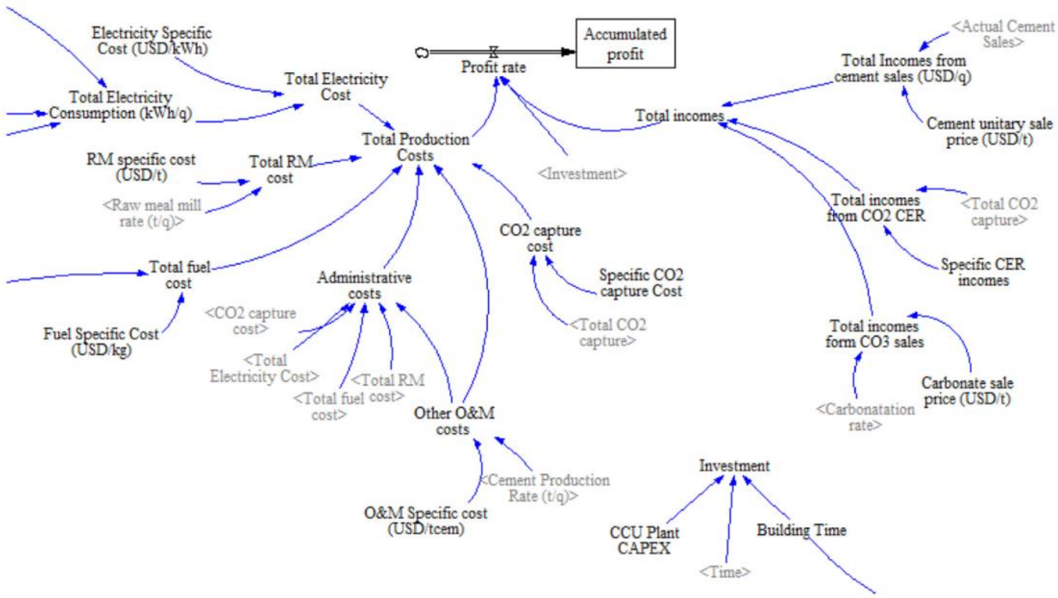

Figure 7 Costs and Income in System Dynamics (Proaño et al., 2020)

Models of consumption changes are common in these dynamic TEAs as they help to understand the price changes over time that can be expected for the various products. Additionally, it is concluded that the dynamics for different REE product markets may be useful for evaluating the price dynamics but for the price, as it pertains to supply, as REEs are co-mined, the supply of REEs is often well correlated (Deng et al., 2021). Earnings before interest, tax, depreciation, and amortization (EBITDA) have also been used as an economic performance metric (Nguyen et al., 2017).

2.1.3.1.7 Sensitivity Testing in SD TEAs

Sensitivity testing is common practice in both TEAs and system dynamics models. Most approaches analyzed that use a system dynamics model within their TEA do not use the capabilities built into common system dynamics software but instead use a pre-defend set of parameters as inputs to the model (Deng et al., 2021; Fazeli et al., 2022;

Laurischkat & Jandt, 2018; Proaño et al., 2020; Yu et al., 2019). This is not to say that the parameters chosen are not run though the SD model because in many cases they will be an input used by the model, just that the capability provided by dynamic simulation tools is not used. One study did make use of the Monte Carlo sensitivity analysis options available when using system dynamics tools (Elizondo-Noriega et al., 2021).

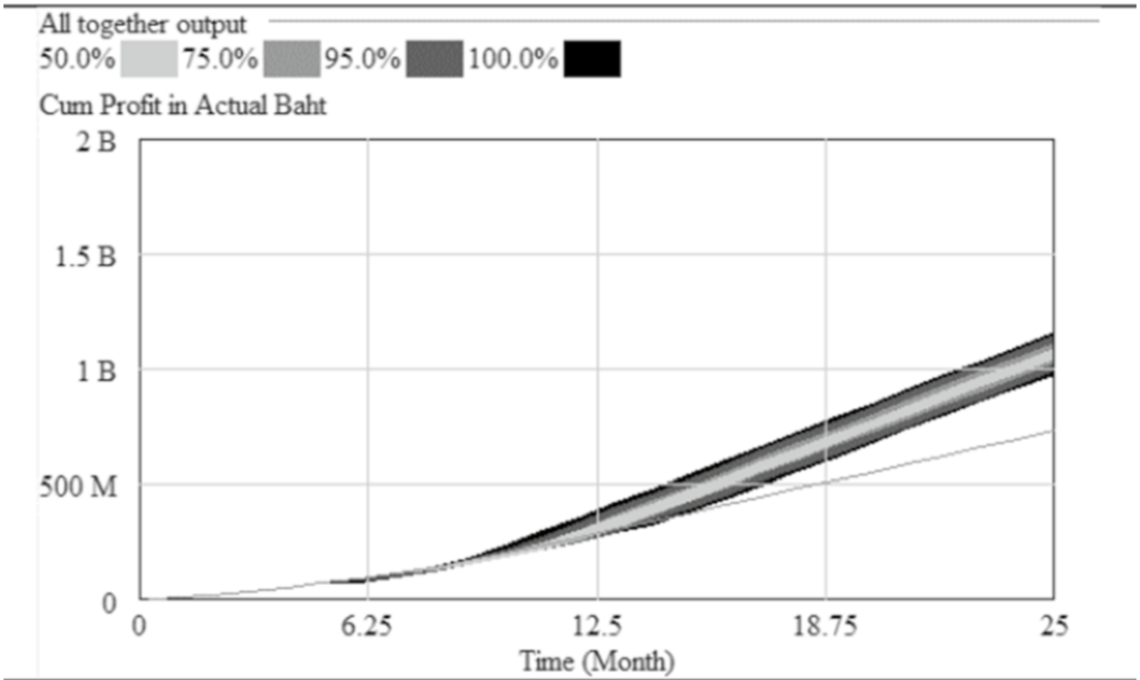

Figure 8 Sensitivity Analysis Output from Dynamic Model (Elizondo-Noriega et al., 2021)

Another did not mention specifically using the built in sensitivity analysis capability of the dynamic modeling tool but the results implied it was used to define the range of EBITDA that is possible with various feedstock and product pricing (Nguyen et al., 2017)

2.1.3.1.8 User Interface in SD TEAS

No studies using system dynamics discussed the user interface of the TEA despite that being a common aspect of system dynamics models and TEA models (Burk, 2018; J. D. Sterman, 2000). Dashboards and flight simulators have a long history of helping users to interact with and understand complex models and specifically within the system dynamics realm there is a broad set of literature on flight simulators (J. Sterman, 2014)

2.1.3.2 TEA and REE

This study has identified a variety of TEAs that pertain to REE (Alipanah et al., 2020; Araya et al., 2020; Chowdhury et al., 2021; Diaz & Lister, 2018; Hein et al., 2020; Ismail & Abidin, 2021; Jin et al., 2017; Larochelle et al., 2021; Liu et al., 2021; Pindar & Dhawan, 2021; Udayakumar et al., 2021; Volkmann et al., 2018). This is important to consider as it identifies how TEAs in this industry are presented and what the rare earth industry considers when thinking about economic and technical performance.

2.1.3.2.1 Process Model in REE TEAs

These TEAs are conducted with the standard approach which for all studies involves a process flow diagram or a description of the process along with some statement of the key flow parameters of the process. Process models can be originated form similar processes, such as was done by Array et al. in which technology used on primary rare earth ores is applied to mining waste products by using a similar process but different feedstock (Araya et al., 2020). Process descriptions are also used in place of a diagram or mass flow tables for the process but can also be useful for processes that are not easily diagramed (Hein et al., 2020; Ismail & Abidin, 2021). Schematic process flow diagrams along with a description and some mass flow data of key variables are by far the most common process models provided in TEAs (Alipanah et al., 2020; Diaz & Lister, 2018; Jin et al., 2017; Larochelle et al., 2021; Liu et al., 2021; Pindar & Dhawan, 2021). Although there may be stages in other studies that use process modeling software, there are few that have full process models developed in process modeling software for rare earth TEAs (Udayakumar et al., 2021).

2.1.3.2.2 Equipment Sizing in REE TEAs

In some cases, it was clear how the equipment was sized and what sizing parameter was used for each piece of equipment (Ismail & Abidin, 2021; Thompson et al., 2018). All other studies provided values of the equipment size or did not reference the equipment size specifically (Alipanah et al., 2020; Araya et al., 2020; Chowdhury et al., 2021; Diaz & Lister, 2018; Hein et al., 2020; Jin et al., 2017; Larochelle et al., 2021; Liu et al., 2021; Nguyen et al., 2017; Pindar & Dhawan, 2021; Udayakumar et al., 2021; Volkmann et al., 2018). Although the general process is described by Liu et al. as sizing the vessel or reactor from the desired flow rate and necessary residence time which then allows the estimation of a purchased cost based on that design, and finally that purchased cost can be converted to current dollars using the Chemical Engineering Plant Cost Index (Liu et al., 2021). They continue that they used an exponential scaling constant of 0.6 for scaling equipment costs based on the size of individual pieces of equipment (Liu et al., 2021).

2.1.3.2.3 Capital Costs in REE TEAs

As defined by Araya "capital costs, also referred to as capital expenses or CAPEX, represent the investment made for the project, which includes costs of the development phase which, among other costs, comprises the purchase of the equipment, building a manufacturing plant and the cost of product launch" (Araya et al., 2020). In the studies where detailed capital costs are provided, the estimate starts with an estimate of the major equipment costs and then each of the previously stated components of the cost are created by using factors of that initial equipment cost which is described by Larochelle; the major equipment costs are estimated with the assumption of building a new industrial facility. They recommended quotes but accept that experienced estimates of equipment cost may be used. Then they apply the Peters and Timmerhaus approach to estimating the other direct costs although budgeted values or recent data from recent projects are used to estimate the costs. Finally, they account for indirect costs based on the nature of the project and add on owners' costs as deemed appropriate by the design engineer (Larochelle et al., 2021). This approach was taken to some degree for all but two of the studies in this analysis (Jin et al., 2017; Volkmann et al., 2018). The ranges of the other direct cost parameters for several studies are shown below and it is noted that the ranges depend on the nature of the process and the types of components needed for that process (Larochelle et al., 2021).

Table 4 Direct Cost Factor Comparisons
Adapted from (Udayakumar et al., 2021) and (Larochelle et al., 2021)

Direct Costs	(Udayakumar et al., 2021)	(Larochelle et al., 2021)
Piping	35%	20% to 70%

Instrumentation and Controls	40%	10% to 20%
Electrical	10%	10%
Building	45%	20% to 30%
Property improvements	15%	10%
Utilities and Facilities	40%	20% to 50%

2.1.3.2.4 Operating Costs in REE TEAs

Operating costs, or OPEX, are the continual costs of operation of a process or technology as well as any end-of-life costs associated with salvage, and they depend greatly on the types of processes that are being analyzed and how the type of accounting is used by the organization. Due to the general similarity of REE processes many of the operating expense breakdowns are roughly the same but it is worth noting the differences. One study provides the cost of each step of the production process as a portion of their operating cost which allows for an analysis of the impact on the profitability of each stage of the process (Pindar & Dhawan, 2021). Some form of material cost shows up in all the studies determined to be related to rare earth elements and in most cases, the breakdown is by chemical or feedstock components used in the process. Utility costs, either broken down or lumped as one element are also common in the analyzed TEAs. In several studies, there are costs noted as general and indirect costs (Alipanah et al., 2020; Chowdhury et al., 2021; Jin et al., 2017; Thompson et al., 2018). Burk defines general operating costs as not directly related to making the process work but necessary to include in a thorough economic analysis (Burk, 2018), things such as “administration, financing, marking, and research and development” while indirect costs encompass “property taxes, insurance, fringe benefits, and overhead” (Chowdhury et al., 2021). Labor is also a common element of operating costs. In some cases, it is broken out by various functions of the labor such as directly related to the process and indirect labor that would be for supervision or other aspects of the business (Alipanah et al., 2020; Liu et al., 2021; Volkmann et al., 2018). Other studies identify operating costs unlikely such as waste management (Alipanah et al., 2020) or spare parts for capital equipment (Larochelle et al., 2021).

Table 5 Cost Estimation Methods for Various Cost Categories (Thompson et al., 2018)

Cost Category		Cost Estimation Method
Other Direct Cost	Operating labor	Required number of people* Labor wage
	Operating supervision	0.2*Operating labor cost
	Quality control	0.15*Operating labor cost
	Maintenance material	0.018*Total fixed capital
	Operating supplies	0.0075* Total fixed capital
Indirect Cost	Fringe Benefits	0.22*(Operating labor + Supervision)
	Overhead (less fringe benefits)	0.5* (Operating labor + Supervision)
	Property taxes	0.02* Total fixed capital
General Cost	Administrative	0.045*A*
	Marketing	0.135*A*
	Research and Development	0.0575*A*
A*=∑ (Raw Material Cost +Utilities Cost + Direct Cost+ Indirect Cost + General Cost)		

2.1.3.2.5 Income in REE TEAs

In the case of rare earth elements, the aspect of pricing is key as it is one of the main drivers of revenue. Pricing in several studies was taken as an average value for the studied rare earth oxide prices and then discounted based on the planned products being of lower quality or as a mixed oxide that would still have to be separated. Other studies used average values of rare earth oxide pricing from the past as the basis for the planned product pricing (Diaz & Lister, 2018; Jin et al., 2017). In several of the studies, there is also another product in the form of either other metals or some other byproduct of the intended process that, similar to the rare earth oxides, a price is chosen and is used to estimate the revenue from that stream (Diaz & Lister, 2018; Nguyen et al., 2017; Volkmann et al., 2018).

2.1.3.2.6 Economic Metrics in REE TEAs

A simple approach to the evaluation of the economics performance of a project is to look at revenue, profit, and profit margin. This approach is taken by several papers without additional alternative economic evaluation methods (Chowdhury et al., 2021; Hein et al., 2020; Jin et al., 2017; Nguyen et al., 2017). Net present value (NPV) is used to evaluate the current value of a potential steam of payments over some number of years at a given interest rate (Vanek et al., 2022). The NPV of projects is used by several of the REE TEAs to evaluate the value of the investment into what are mostly high capital projects (Alipanah et al., 2020; Araya et al., 2020; Larochelle et al., 2021). With the NPV calculation, the concept of internal rate of return can be used as an additional economic metric, where the internal rate of return is defined as the interest rate such that the NPV is 0 (Vanek et al., 2022) and this is another common metric of the rare earth projects, especially once an NPV is being calculated (Araya et al., 2020; Larochelle et al., 2021; Liu et al., 2021; Volkmann et al., 2018). Finally, another simple method used to demonstrate the economic performance of the projects is a payback period which is the number of years it takes for the profit to pay back the initial investment (Ismail & Abidin, 2021; Thompson et al., 2018; Udayakumar et al., 2021; Volkmann et al., 2018).

2.1.3.2.7 User Interface in REE TEA

We did not find any specific references to the user interface or dashboards used in the studied TEAs. Much like in system dynamics, user interfaces are a key aspect of communication for TEAs (Burk, 2018), however, the lack of recommendations or even examples of user interfaces leaves this as an area of development for TEAs both within and outside of the rare earth element space.

2.1.3.2.8 Sensitivity Testing in REE TEAs

As described by Burk, sensitivity analysis looks at how changes in input parameters change the outcome of the TEA and provides value in understanding where are areas that additional optimization would make a large benefit or areas where risks are high due to the sensitivity of the outcome based on a parameter (Burk, 2018). Many of the rare earth element TEAs perform sensitivity testing and one of the most common elements changed is the rare earth product pricing. The price parameters are varied based on historical data ranges (Chowdhury et al., 2021) or ranges determined to be reasonable by the authors (Araya et al., 2020; Jin et al., 2017; Larochelle et al., 2021; Nguyen et al., 2017; Thompson et al., 2018; Volkmann et al., 2018). Additional sensitives to various capital costs or operating costs are also used in the rare earth TEA. These can be at a high level of just a range on the overall CAPEX and OPEX (Araya et al., 2020; Diaz & Lister, 2018) or on specific feedstock or consumable costs (Jin et al., 2017; Larochelle et al., 2021; Liu et al., 2021; Nguyen et al., 2017; Thompson et al., 2018; Udayakumar et al., 2021). Another area of sensitivity analysis is to process parameters that may impact the overall economic success of the project, the details of which are very process specific but are a common area of sensitivity analysis in the rare earth TEAs (Hein et al., 2020; Thompson et al., 2018; Udayakumar et al., 2021). In general, the ranges used in a sensitivity analysis can be chosen based on historical data as mentioned above with pricing or based on statistical distributions and a Monte Carlo analysis can be performed (Larochelle et al., 2021)

2.1.4 Gaps in SD and REE TEA Research

Techno-economic analyses are used in the evaluation of novel processes and possess several common components. The analysis is time based and inherently depends on the behavior over time of a variety of processes. Standard TEAs keep many parameters that may change over time as static assumptions in order to simplify the analysis. These components and parameters show up in some form in existing standard approach TEAs related to rare earth element production. Approaches to the development of these components also maintain some common methods in the typical approaches. System dynamics has been applied in several cases to techno-economic assessment as well, often as one or multiple of the standard TEA components. Combining these various methods can provide the benefits of a dynamic model as seen in several of the system dynamics containing TEAs to an overall TEA while still providing the commonly used inputs and outputs of standard TEAs.

2.2 System Dynamics for Business Modeling

As explained in Strategy Dynamics Essentials, Kim Warren states that strategy decisions in business are inherently dynamic and contain feedback effects. He continues that this is true for organizations of all sizes and many goals within those organizations, including small businesses. Throughout the text, he explores how modeling the nature of the business problem and gaining insight into what strategic choices will lead to what desired outcomes is the core focus of the strategy modeling resources (Warren, 2010).

2.2.1 Management Flight Simulators

A common tool that is developed to communicate the model and outcomes is a management flight simulator. These allow decision makers to make decisions as they would in the real world and see the outcomes of those decisions as predicted by the simulation (J. D. Sterman, 2000). Rather than a direct/static recommendation informed by a model, these allow for seeing the assumptions and turning the “knobs” in a visual format that can be used by people at various levels in a group to explore the model and the system they are working in. Examples of these types of simulators make the purpose and method clear as explored by Sterman with the use of these types of flight simulators as tools for exploring various markets. He describes the use of flight simulators for a commodity pricing problem, learning curve analysis, competition between firms, the tragedy of the commons, building a start-up company, and global climate negotiations(J. Sterman, 2014). The span of these examples shows how broadly applicable these types of tools can be and provides a wide range of examples of how such an implementation can help the understanding and operation of a complex model.

These simulators have been described as “compressing time” such that feedback loops that are typically separated by time and space can be observed in a timescale that learning can happen in real time (Papageorgiou et al., 2008).

The stage in the modeling process where management flight simulators (MFS) are built comes after the modeling phases have been completed, although feedback from the use and operation of the model via the MFS can be feedback through the modeling process. This is shown by the adapted diagram by Papageorgiou.

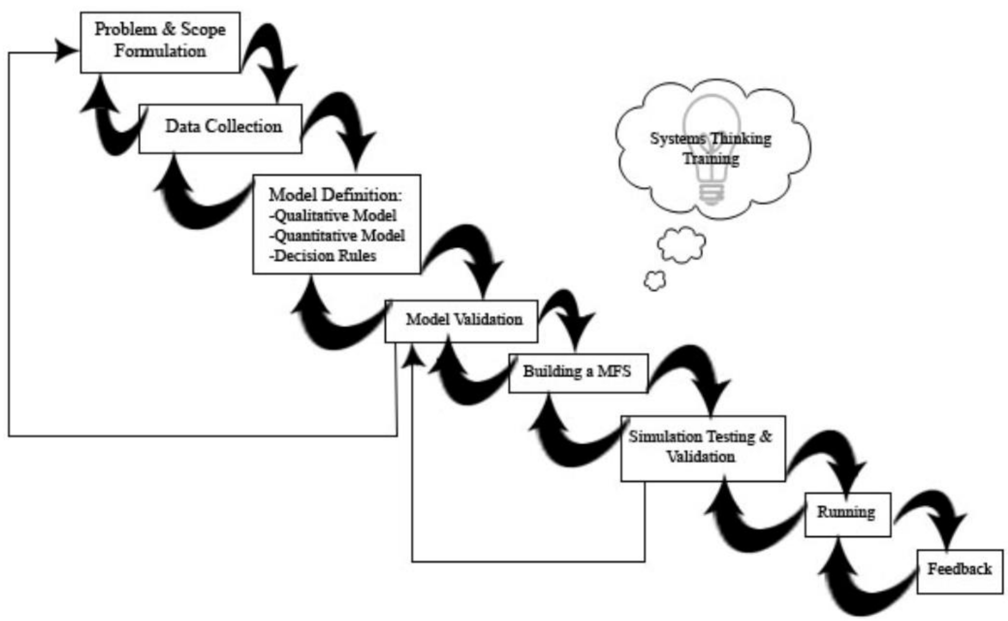

Figure 9 Framework for SD model Development including MFS (Papageorgiou et al., 2008)

This conceptual framework for developing system dynamics management flight simulators (MFS) is a generic method for the development of simulators allowing for scenario testing for helping to solve management problems in systems with feedback. The final result of the MFS effort is to have a series of decisions and results arrayed such that users of the MFS can see the results of their decisions in near real time even if they are delayed and spread over many years in the real system (Papageorgiou et al., 2008).

2.2.2 Project Modeling in System Dynamics

Project modeling has been described as one of the most successful applications of system dynamics (Lyneis & Ford, 2007). The four groups of a model structure that are represented in the common project models are typical project features that appear in the real world, the rework cycle, project control mechanisms, and ripple and secondary effects of those control mechanisms (Lyneis & Ford, 2007). This approach has been applied across industries and often for large, complex projects (Lyneis, 2004). Lyneis et. al. describe a technique that has been used is applying project modeling to the pre-project phase in the biding or planning stage, risk analysis, and mitigation analysis (Lyneis et al., 2001). They express how these tools are applied in such a way to evaluate ethe feasibility of a schedule or budget given various project assumptions such as schedule, scope, or budget. They further recommend that similar projects within the organization are used to evaluate typical approaches where possible and if that is not possible the model can be used to assess the assumptions required to make the project successful (Lyneis et al., 2001). This approach can provide a necessary evaluation of the plan developed for TEAs for the initial construction and start up phases of a process which will likely have the same characteristics as many other large projects. In some cases, the type of project being executed in the TEA will be one that is novel and may not have easy comparisons to past projects for the source of data. This is not an unknown issue to TEAs which make use of factors and standard relationships in many aspects of the estimation of the overall project feasibility. A general model structure that can be applied to projects of the type that appear in TEAs is found in (Reichelt & Lyneis, 1999) with many of the feedback effects found to exist in complex projects shown.

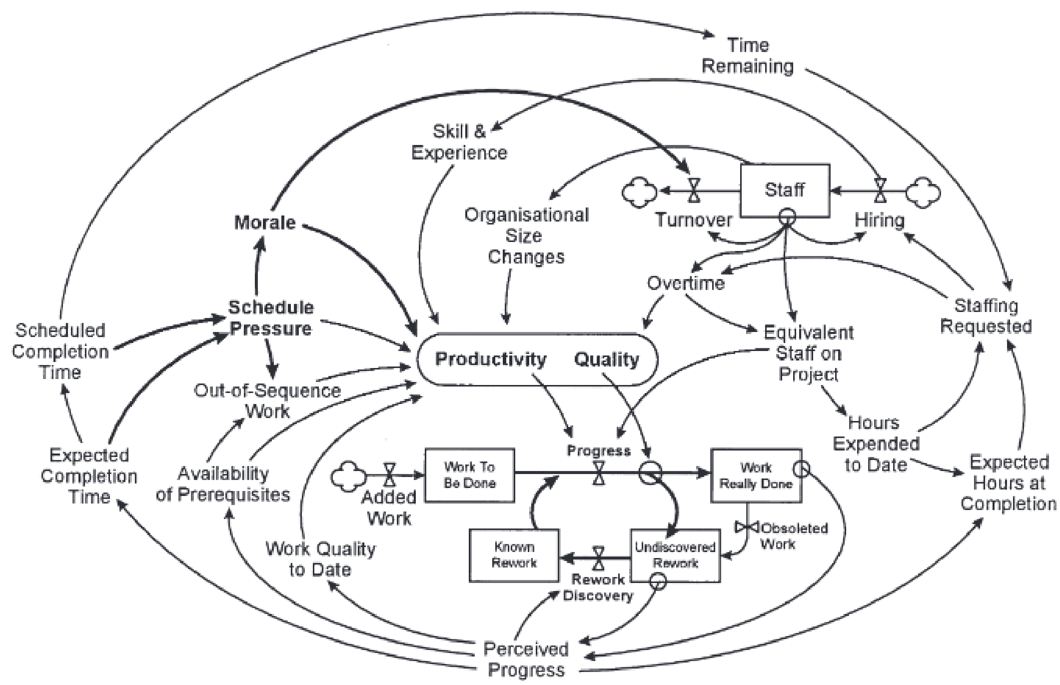

Figure 10 Feedback Effects in Complex Projects (Reichelt & Lyneis, 1999).

Additionally (Reichelt & Lyneis, 1999) evaluated 10 projects in aerospace, shipbuilding, and construction for budget overruns and estimates of effort spent on rework. They found that there was an average budget overrun of 75% and only three of ten had under 25% budget overrun while regarding schedule they found an average of 53% overrun. This was determined by them to be due to a large fraction of the design and build hours being spent on rework, specifically an average of 48% of design hours being spent on rework and 24% of build hours being spent on rework. Utilizing the model, they were able to determine that the average quality of work was 0.33 which indicates that each piece of work was is redone three times during the project. They further provide some indicated averages of various effects on quality and productivity in the design and build phases that are included in the model structure (Reichelt & Lyneis, 1999).

2.2.3 Commodity Pricing Model

As discussed in the literature review of TEAs, dynamic pricing models are an area of research that is being explored to improve the outcome of TEAs. The approach to developing a pricing model is very specific to the type of product being created and the market it is consumed by. In the case of rare earth elements, a hypothesis of a potentially similar market is that of other non-ferrous metals. The work done by (Glöser-Chahoud et al., 2016) connects raw material markets and commodity pricing via the changes in the supply of the commodity. They proposed a model structure that creates the oscillatory nature of commodity prices due to a delay in capacity creation relative to demand and price changes. For the global copper market, they found that the demand was well correlated with the global gross domestic product, indicating that copper demand increases as there is economic growth to consume copper. And showed a higher price expectation for the future relative to other predictions.

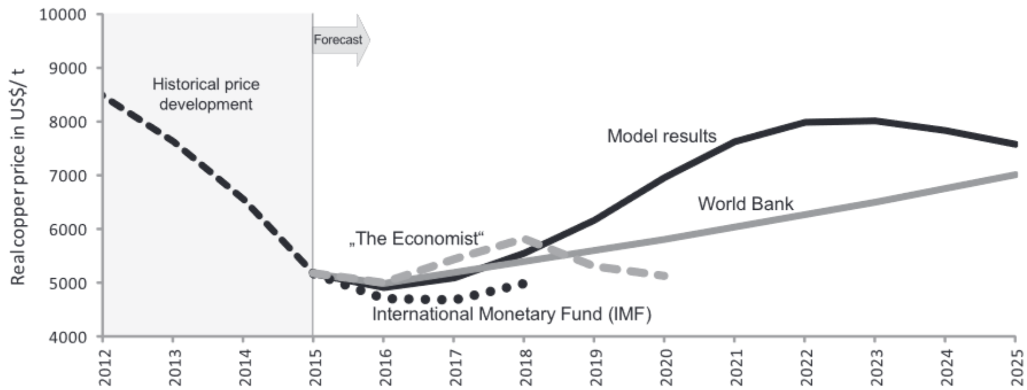

Figure 11 Comparison of Various Forecast Results for Copper Market(Glöser-Chahoud et al., 2016)

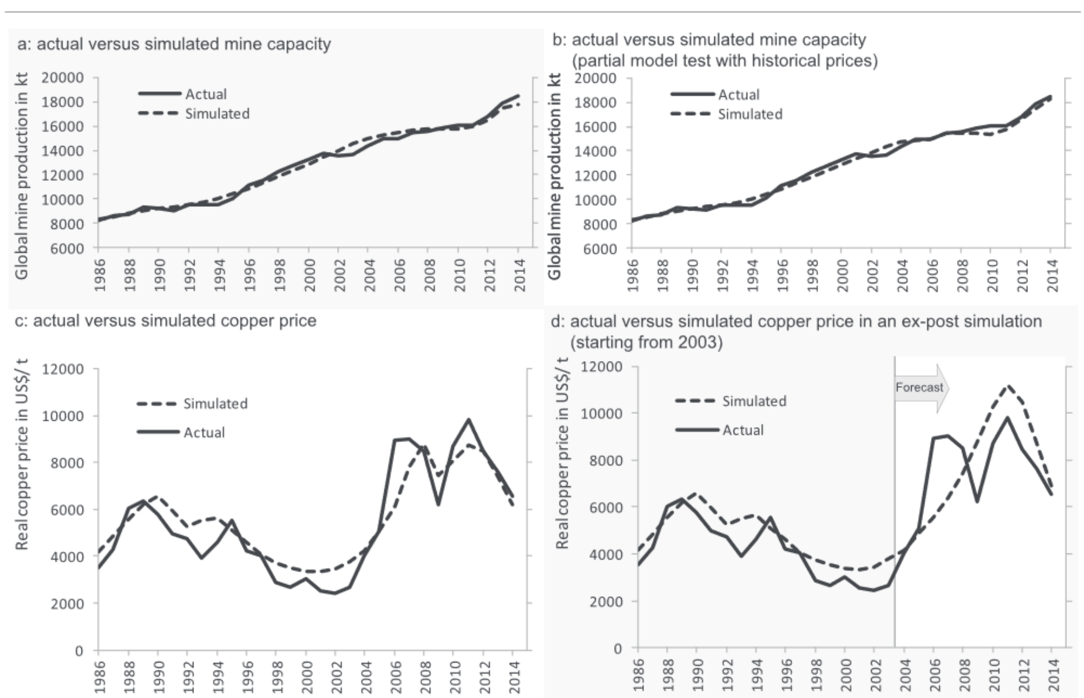

Figure 12 model Simulation and Calibration Results for Copper Market(Glöser-Chahoud et al., 2016)

Their effort to calibrate the model to historical data showed that a simple commodity pricing model can replicate the past behavior of a market(Glöser-Chahoud et al., 2016). As with other system dynamics approaches a sensitivity analysis on the pricing dynamics moving forward is also easily applied which is a very relevant parameter for TEAs.

2.2.4 Hiring Model in System Dynamics

The focus of TEAs is on the technical and economic aspects of a project but those are not the only metrics by which to evaluate if a project will meet the stakeholder's goals. Increasingly there is a focus on other social aspects of projects such as job creation as that will impact the local economy (Kamal-Chaoui, 2022). As part of the TEA there is typically an estimate of the labor required for the project but the nature of how that labor is supplied over time and what kind of labor pool may need to exist to support the labor need is not typically within the TEA. These considerations fit nicely in the system dynamics framework and the core structure of this type of hiring chain is a common model structure (Hines, 1996). The application of this common modeling structure can allow an assessment of how the labor force will grow, what kind of hiring and retention policies may be needed to maintain a sufficient workforce, and the implications of non-ideal conditions. A simple hiring change structure can be used as the starting point from Hines.

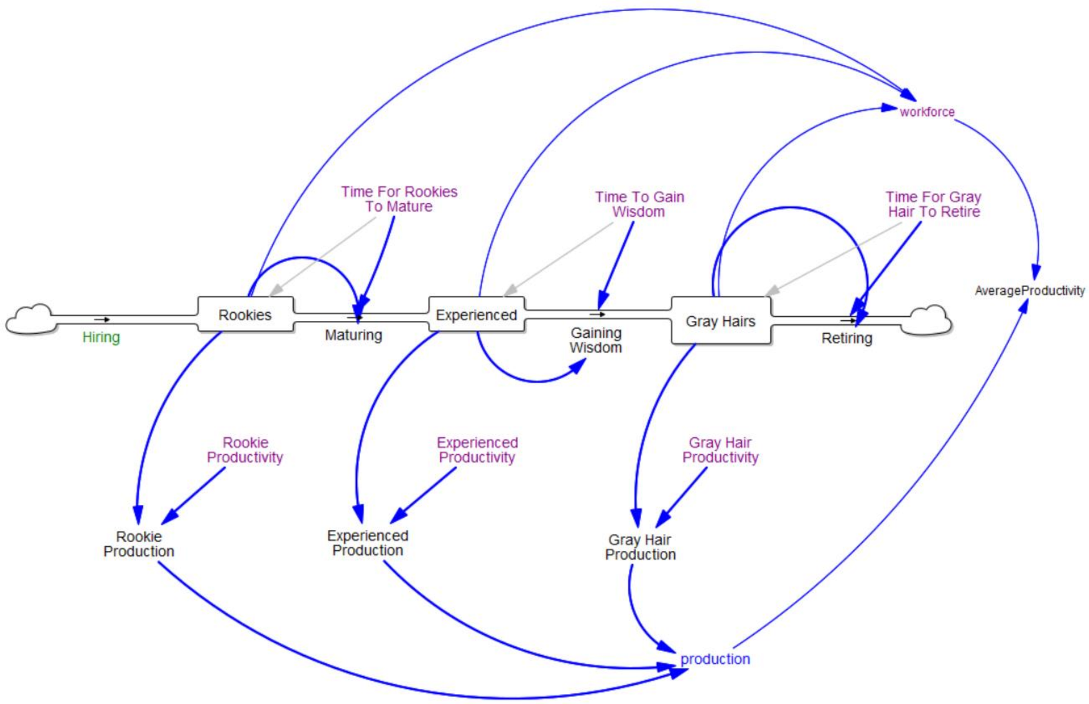

Figure 13 Template Model for Hiring and Experience Chain (Hines, 1996)

As this is a template for how people move through the process of gaining experience modifications may be needed to address the needs of a TEA. As TEAs are focused on a specific process and not a company, there may need to be added consideration as to how people move out of working on the process rather than retirement from an organization. Similarly, TEAs must consider the time from when the spending occurs on the investment and when revenue starts and onward but for revenue to start not only is the process construction and commissioning needed to be complete but also a workforce to run the process to earn the revenue is needed. These types of considerations allow for a compact but effective model of the hiring process to be conducted which validates that enough people will be available to operate the process when they are needed.

CHAPTER 3

3 RESEARCH METHODOLOGY

3.1 Introduction

As described in Chapter 1, this work intends to apply system dynamics modeling to the TEA process and incorporate elements not typically considered but relevant in practice to the TEA. This application uses literature to guide the generic structure and applies that structure to a specific case for the rare earth extraction process.

3.2 Data Collection and Analysis

Various forms of data support this research effort. As described below, different approaches have been used to address different areas of the problem.

3.2.1 Data from Literature

To evaluate what elements are typically included in a TEA, how they are used, and what is missing the detailed review of the TEA literature was conducted as described in Chapter 2. This provided a framework for what is the usual approach, especially as it pertains to REE related TEAs. Additionally, evaluating how the element of TEAs are described and applied from engineering texts supported the research effort into what are the typically included components of a TEA and how are they typically implemented.

In addition to standard approaches of TEAs, an investigation into applications of dynamic modeling to TEAs provided a view into how this problem has been approached by others. Additionally, past research on business modeling from the system dynamic literature provides applications that could be useful or relevant for inclusion within a TEA. Literature from various sources was also used to parameterize the model components from the system dynamics literature as it pertained to the REE aspects of the case study.

3.2.2 Data from Past TEAs

Another source of data for this work is past TEAs on the rare earth process as well as other TEAs that were built for different processes. These various TEAs were built in spreadsheet software, some being supported by process modeling from other tools. An evaluation of the approach used in these TEAs provides a means of comparing the research on spreadsheets to technical spreadsheets. Additionally, the spreadsheet TEAs for the REE process provided direct comparisons for two TEAs developed for the same process but at different stages of development. In the case of dynamic models, one form of data is the relationship between variables that make up the system and thus the previously developed TEAs provide a wealth of data to support the modeling on assumptions and connections in the dynamic modeling.

3.2.3 Data from Modeling

In addition to the data above which can be used to develop the model, the model itself produces data. The model results are relevant sources of data when evaluating the research questions.

3.2.4 Analysis

In order to validate the dynamic approach used, several forms of analysis are conducted. First is a comparison of the model results to the provided TEA results for differences and sources of those differences. This approach helps identify areas where errors or different assumptions exist in the spreadsheet-based TEA. Second is comparing the model results with the spreadsheet TEA results with regard to the sensitivity analysis as that allows for understanding any alternative potential TEA outcomes that may be likely given a broader set of considerations.

3.3 Modeling Approach

A generic model is developed that matches the components identified in the literature review. This model is intended to provide a simple example of what calculations are used in a TEA and how they can be implemented in SD. This generic model is then applied to several of the TEAs of the REE extraction project. This is done by modifying the generic model to match what exists in the REE TEAs. In some cases, this is a set of parameters but in general, some modifications to the structure of the model are required to align it with the intent of the REE TEAs. This process is what would be needed if the generic approach is applied to other processes. The generic TEA equations, units, description, and source of content are provided in Appendix B.

3.3.1 Application of Generic Model

T application of the generic TEA to a specific process is focused on three areas the process model, the equipment sizing/scaling, and the parameters used for the various elements of capital and operating costs. In the application of the generic model to the

REE projects, two separate process model approaches are used. One is to attempt a more representative model using a stock and flow diagram of the process with the mass and energy flows and unit operations. The second is much simpler and thus misses some of the nuances in the process but allows for an evaluation of the added SD components and their changes to the outcome.

The added SD elements include a project model, a pricing model, and a hiring model. These components are applied from existing literature and incorporated into the REE dynamic TEA. The method by which they are included is described further in Appendix C along with the equations, units, description, and source of any relevant parameters used.

3.3.2 General Steps of Application

In general, the application of this model approach to an existing TEA or a process where a TEA would be relevant requires the same general steps, which are also consistent with the steps described as relevant for a standard TEA approach (Gargalo et al., 2016). This involves specifying the goal of the analysis, in this case, the economic potential of the process at a specified scale. Then a process model component must be built depending on the nature of the process. In the simple process model case of the REE TEA, conversion of raw material to product and ratios of various process parameters from that raw material flow were used. Following the process parameters definition, the equipment sizing can be performed based on engineering principles relevant to the equipment. Examples of pump, vessel, and heater sizing are provided in the generic dynamic TEA, but additional complexity will be required to size all key components of other processes. One the process parameters and equipment sizes have been specified, the equipment cost can be estimated by scaling parameters as is common in these types of analysis (Burk, 2019; Peters et al., 2003; Turton et al., 2003) but engineering judgment will still need to be applied. Equipment costs can also be entered from quotes from suppliers or other projects if that is available. The equipment cost can then be used as the starting point for the capital cost estimation in which factors from experience or research can be used to account for the additional direct and indirect costs. Then the process flows and costs of materials can be used to estimate the operating expenses along with factor form experience or research to support the non-direct operating expenses. The income potential of the process depends on the product price and product flow. The flow comes from the process model and the price from research or other modeling as demonstrated in the REE case, although product pricing models need to be approached with caution as nuances in product price can be important for the economic performance and sizing of a process. Finally, the economic metrics can be evaluated by looking at the costs and incomes of the process and using prebuilt calculations for NPV, IRR, ROI, or payback period. Other economic metrics such as net cash flow or profit can be reported as well from the model.

3.4 Summary

The described modeling approach was applied to the REE TEAs, along with the data available from TEA research to support this work. This includes the development of the generic dynamic TEA approach, application of SD elements, error investigation, and comparison of overall results of the application of the dynamic TEA to the REE TEAs. Additional details of the species of the methods are included in the Appendices but the general approach discussed supports the obtained results.

CHAPTER 4

4 DYNAMIC STRUCTURE OF STANDARD TECHNO-ECONOMIC ASSESSMENT

Based on the review of the literature, there is a set of components that are relevant to TEAs in general and rare earth element processes specifically. Additionally, system dynamics approaches have touched on various aspects of the TEA approach which can be combined into a representation of the standard TEA approach in a dynamic model. The dynamic approach will allow for feedback between the components of a standard TEA as well as being able to use other elements of dynamic modeling to improve confidence in the outcome of the TEA.

4.1 Generic Dynamic Process Model

The process model is very dependent on the type of process and a purely generic process model may not be broadly applicable enough to have a lot of value. Considering some of the ranges of the types of process models that may exist in general may help to guide work on specific applications. The simplest approach that could be used is a list of process parameters that are specified for the process. This is like several process models identified in the literature where the process parameters were provided as static values for the process (Elizondo-Noriega et al., 2021; Proaño et al., 2020). From a dynamic modeling point of view, this kind of approach can be treated as a list of constants for the process. If that is desired as the approach, this could be used as the first step for iterative model development.

An increase in complexity while remaining relativity simple can be setting some key process parameters such as the sizing of the process and then setting all other flows and conditions based on that one parameter. This can be useful to tie the process flows together so if feedback to the process model from other aspects of the model are included, all process parameters can be changed relativity to the key parameter.

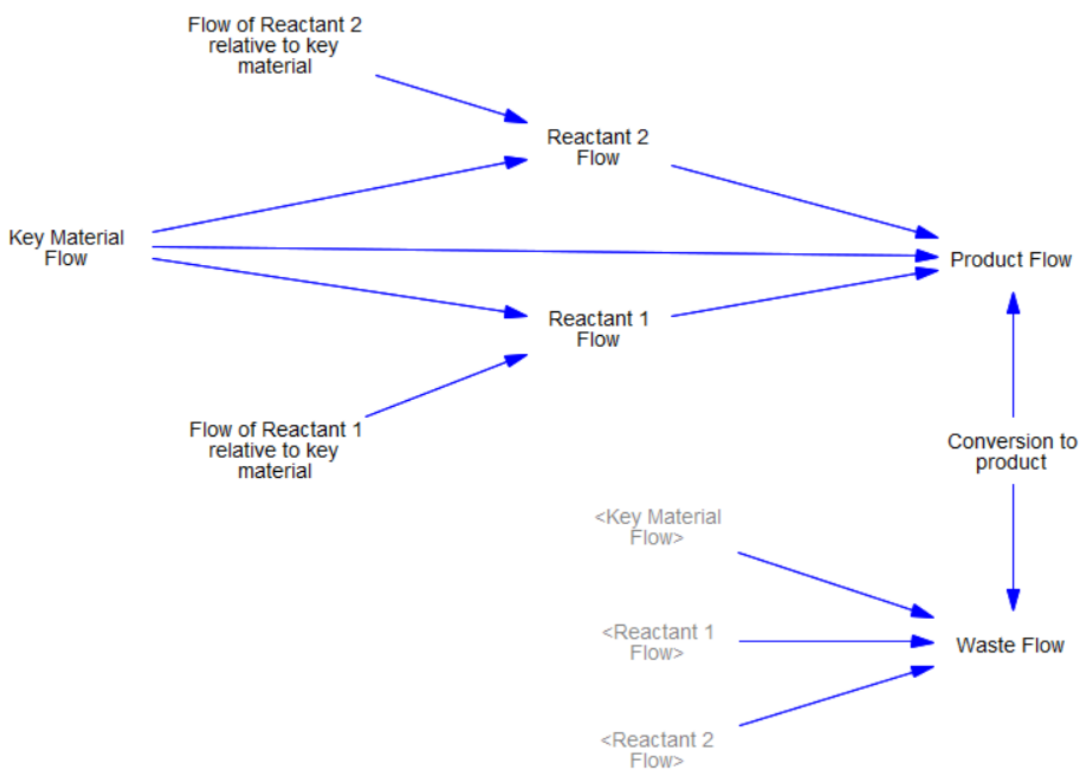

Figure 14 Generic SD Process model

The simple process model uses the key material flow and an estimate of the flow ratio of another reactant to the key material flow to calculate the reactant flow. The sum of all the reactant flows multiplied by a conversion fraction determines the flow of product and the flow of waste is the remainder of the fraction multiplied by the total material flow.

4.1.1 More Detailed Process Models

As additional detail is considered, process models can be increasingly complex. This additional complexity should only be used where it provides value to the modeling effort rather than trying to model the process at a level of detail that will not change the outcomes of the model. A case of this is shown in Chapter 5 where a more process centric model has been developed. Aspects that may be important to consider in the more physically representative models are accumulations in the process, time constants of various process elements, and monitoring the inputs and outputs of the process. This meets one of the requirements of stock which is that they maintain mutual exclusivity while being collectively exhaustive, meaning that material is in only one stock at a time and everything must be captured (Warren, 2018).

4.2 Generic Dynamic Equipment Sizing

Scaling equipment based on the type of equipment and the parameters of the process is a straightforward approach from a technical point of view. These sizing elements can be interconnected to the process flow parameters and are used by capital cost calculations. Three common equipment sizing approaches are explored within the dynamic structure. These are vessel sizing, pump sizing, and heater sizing. All three of these depend on the process parameters and utilize engineering calculations to develop the equipment needed.

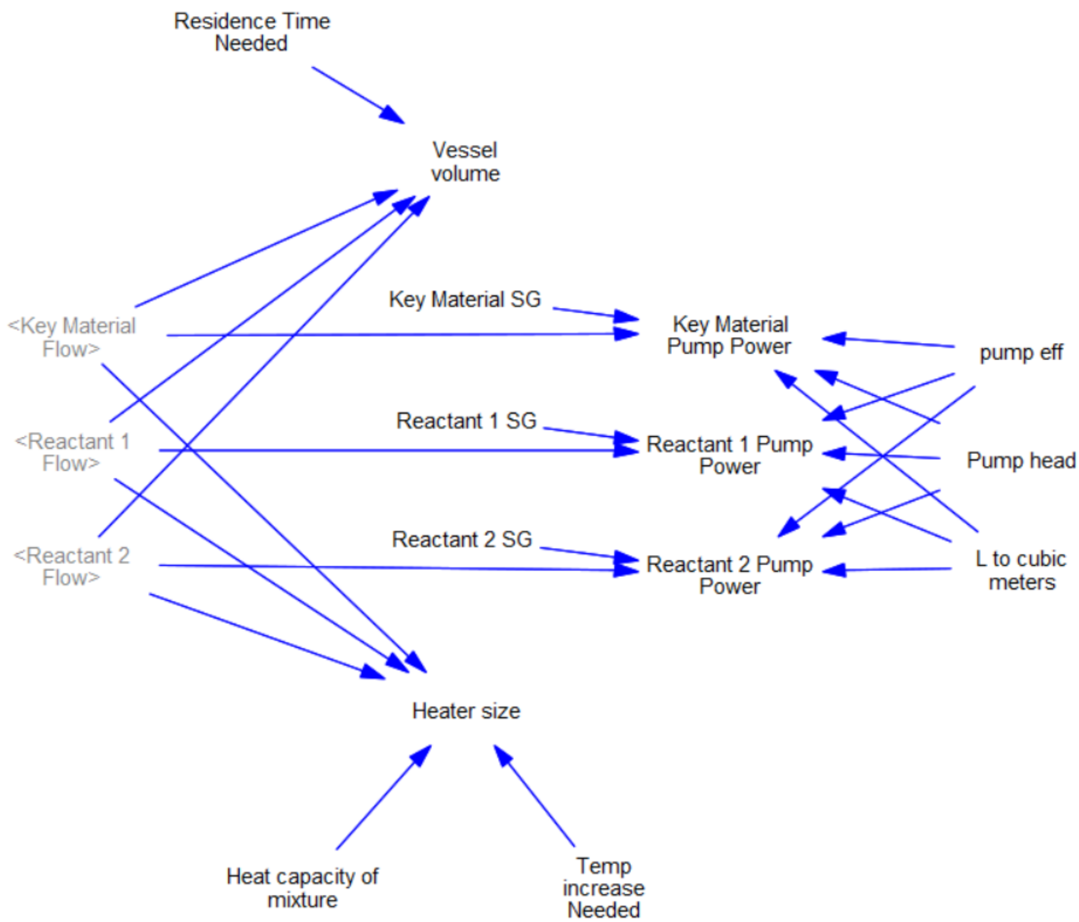

Figure 15 Generic SD Equipment sizing

This forms a simple basis for how equipment sizing can be computed using engineering principles within the dynamic TEA. The size of the equipment is a necessary element for specifying the capital cost of the equipment.

4.2 Generic Dynamic Capital Costs

Capital costs are analyzed by the economic cost which is scaled based on process size and then the rest of the CAPEX needed for the process which is estimated from the initial equipment costs.

4.2.1 Generic Dynamic Equipment Cost Scaling

The example TEAs found mainly start with the equipment cost. The equipment cost is based on the size of the equipment and the nature of the process. With the main equipment of the process identified, the cost of the equipment can be estimated by scaling the known cost of a similar piece of equipment to the size determined for this process. As Burk describes (Burk, 2019), costs from quotes, research, or other experience can be scaled to the size of the commercial process based on a capacity parameter. He continues that the capacity parameter is a property of the type of equipment that is being scaled. Depending on the type of equipment there are capacity parameters that are preferable for use in determining the scaling.

Table 6 Capacity Parameters for Types of Equipment from(Burk, 2018)

Equipment Type	Capacity Parameter	Utilities
Pump, Compressor	Shaft Power	Electricity, Fuel
Vessel, Tank, Reactor	Volume	Steam, Cooling Water
Heat Exchanger	Area	Steam, Cooling Water, Refrigeration
Heater	Duty	Electricity, Fuel
Blower	Standard Volumetric Flowrate	Electricity, Fuel

With the capacity parameter defined for the pieces of equipment, scaling exponents can be used based on the ratio of the capacity parameters:

$$Cost_{Desired\ Capacity} = Cost_{Known\ Capacity} \times \left(\frac{Capacity\ parameter_{Desired\ Capacity}}{Capacity\ Parameter_{known\ capcity}}\right)^{Scaling\ Expoenet}$$

Common scaling exponents have been complied by Burk for various types of equipment and plants and additional detail for various process equipment is available in the literature (Burk, 2019; Remer & Chai, 1993).

Table 7 Scaling Exponents For Equipment and Plants (Burk, 2019)

Equipment	Range	Exponent
Blender, Double Cone Rotary, Carbon Steel	1.4–7.1 m^3	0.49
Blower, Centrifugal	0.5–4.7 m^3	0.59
Centrifuge, Solid Bowl, Carbon Steel	7.5–75 kW	0.67
Crystallizer, Vacuum Batch, Carbon Steel	15–200 m^3	0.37
Compressor, Reciprocating, Two-Stage, with 1,035-kPa Discharge	0.005–0.19 m^3/s	0.69
Fan, Centrifugal	10–35 m^3/s	1.17
Heat Exchanger, Shell-and-Tube with a Floating Head, Carbon Steel	10–40 m^2	0.6
Motor, Squirrel Cage, Induction, 440 V, Explosionproof	15–150 kW	0.99
Pump, Centrifugal, Horizontal, Cast Steel	4–40 m^3/s-kPa	0.33
Reactor, Stainless Steel, 2,070 kPa	0.4–4 m^3	0.56
Tank, Flat Head, Carbon Steel	0.4–40 m^3	0.57
Tray, Bubble Cap, Carbon Steel	1–3 m dia.	1.20
Plant	**Range**	**Exponent**
Acetic Acid	3,300–30,000 ton/yr	0.68
Ammonia	33,000–300,000 ton/yr	0.53
Chlorine	17,000–150,000 ton/yr	0.45
Polyethylene	1,700–15,000 ton/yr	0.65

Scaling of equipment costs can be broken down further into considering how various aspects of the equipment scale with different aspects of the equipment. Burk describes how this process can be taken for a vessel and based on the change of the scaling ratio the contribution to the equipment cost changes leading to smaller vessels having their costs elevated due to elements that do not scale with the volume of the vessel (Burk, 2019). This results in the following table and the relationship between the scaling exponent and scaling ratio of the vessel.

Table 8 Example Scaling Exponent for a Vessel (Burk, 2019)

Cost Component	Cost Scales With	Scaling Exponent Relative to Volume	0.1x Scale Contribution to Cost, %	1x Scale Contribution to Cost, %	10x Scale Contribution to Cost, %
Shell Material	Surface Area	2/3	18	35	34
Instrument Port Material	N/A	0	24	10	2
Process Port Material	Volume	1	2	8	17
Support Material	Mass	1	2	8	17
Design Labor	N/A	0	24	10	2
Welding Labor	Length	1/3	16	14	6
Other Labor	Volume	1	2	10	21
Code Stamp	N/A	0	12	5	1

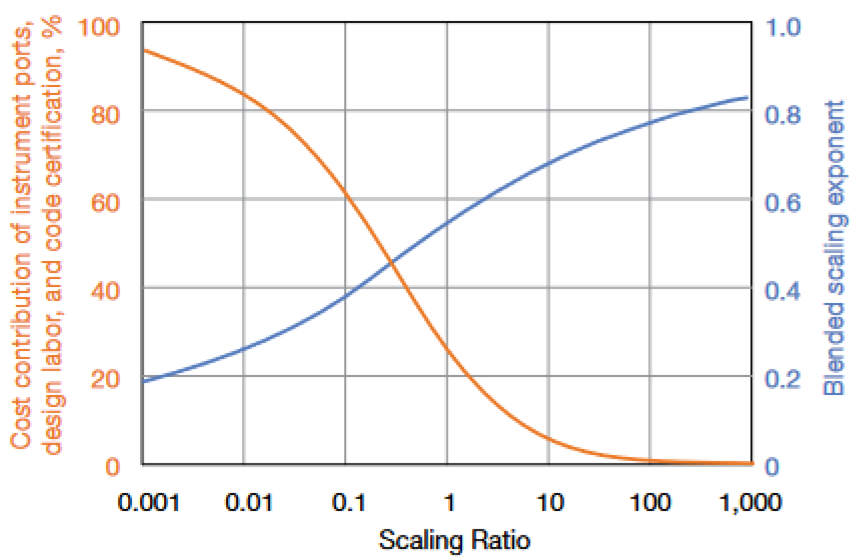

Figure 16 Curve for Scaling Ratio to Scaling Exponent for the Vessel in Table 8 (Burk, 2019)

Based on that consideration there is a typical shape that forms with the curves of scale vs cost as is shown by Burk (Burk, 2019).

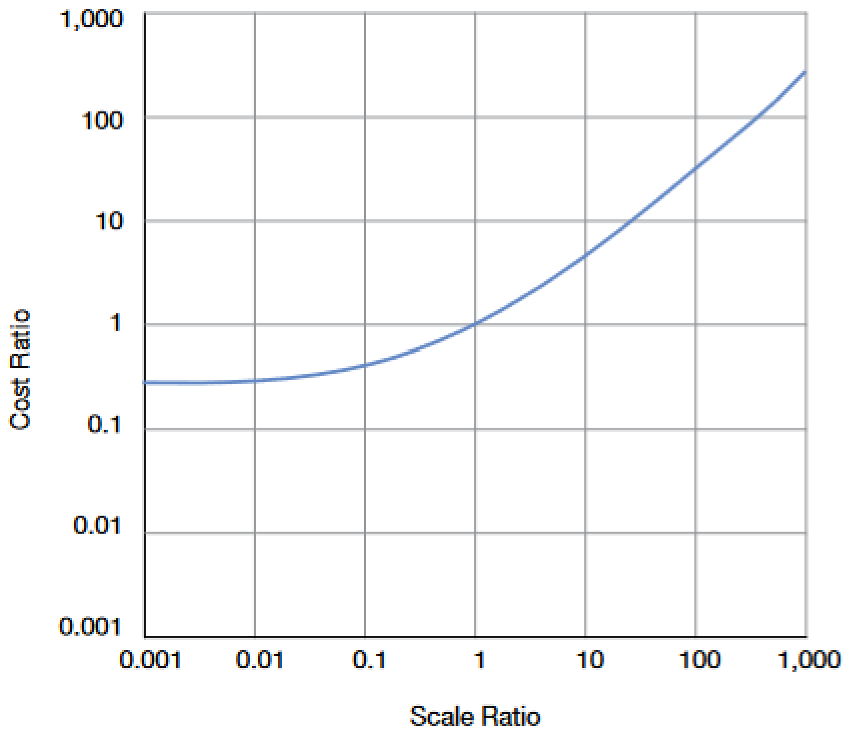

Figure 17 Graph of Cost Ratio vs Scale Ratio for the Vessel in Table 8 (Burk, 2019)

Depending on the level of detail needed to represent the process this can be a relativity simple calculation set in the model where the resulting equipment capital cost is developed using the scaling relationships. On some equipment, such as the pump, the cost scaling can be done with a single scaling exponent whereas others such as the vessel can use a blended scaling exponent as described above.

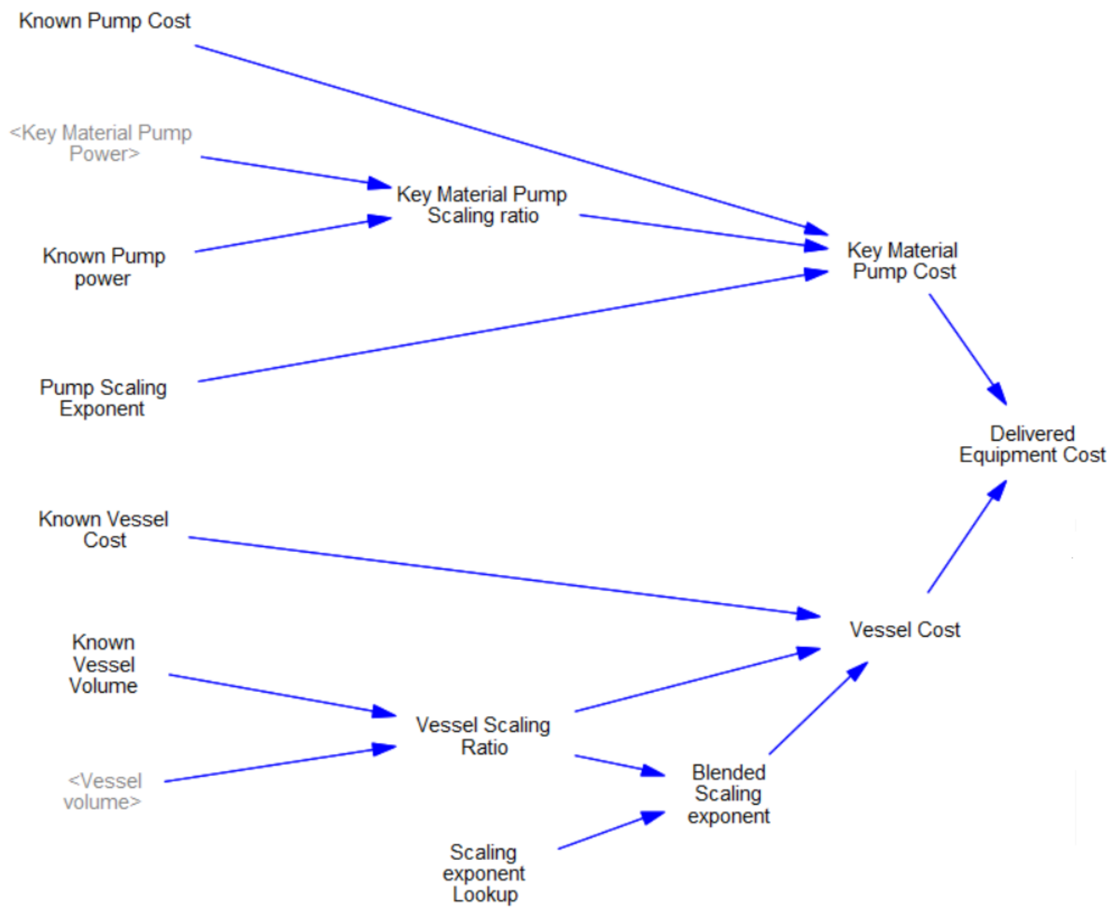

Figure 18 Generic SD Equipment Cost

This model uses a lookup function that aligns with the scaling exponent curve developed by Burk (Burk, 2019). The curve, shown as the lookup points, is used to determine the scaling exponent needed for scaling the vessel cost.

Table 9 Lookup Table for Vessel Scaling ratio vs Blended Scaling Exponent

Vessel Scaling Ratio	Blended Scaling Exponent
0.001	0.2
0.01	0.25
0.1	0.4
1	0.55
10	0.7
100	0.75
1000	0.85

There is an assumed time basis of the cost scaling that is based on when the known cost comes from, which requires an adjustment to today's dollars to make the equipment costs in line with the changes due to the time value of money. This can be done using various cost indices which are developed for this purpose Chemical Engineering Plant Cost Index (CEPCI) or Marshall and Swift Equipment Cost Index where the determined scaled cost is scaled based on the index (Burk, 2018):

$$Cost_{Year\ 2} = Cost_{Year\ 1} \times \left(\frac{Cost\ Index_{Year\ 2}}{Cost\ Index_{Year\ 1}}\right)$$

This scaling across time is simply implemented in a dynamic model but in this case, has not been included in this generic model.

4.2.2 Generic Dynamic Remaining CAPEX

Once the total equipment cost is calculated several approaches can be used to estimate the remainder of the capital costs. Detailed estimates of all the necessary capital costs can be created including the specifics of the material and labor needed for each component of the overall cost. This approach results in the highest accuracy but also request the most effort and knowledge to obtain such a detailed estimate (Peters et al., 2003).

Another approach that was taken in several TEAs from the literature was to use factors relative to the equipment cost. There are a fair amount of assumptions built into these factors which results in a lower accuracy estimate but can be much faster than a detailed estimated (Peters et al., 2003). This approach is well suited for dynamic modeling as the values are tied to the equipment cost so if there are changes in equipment costs there will be changes to the overall capital costs. Similarly, it allows for other values to be used for specific costs which may be available or easily estimated and others can be kept as a factor-based approach.

Initially, the direct costs can be determined from the equipment cost with factors related to different aspects of the direct costs. The factors utilized depend on the type of process but general starting points have been developed and are documented in Peters et al (Peters et al., 2003).

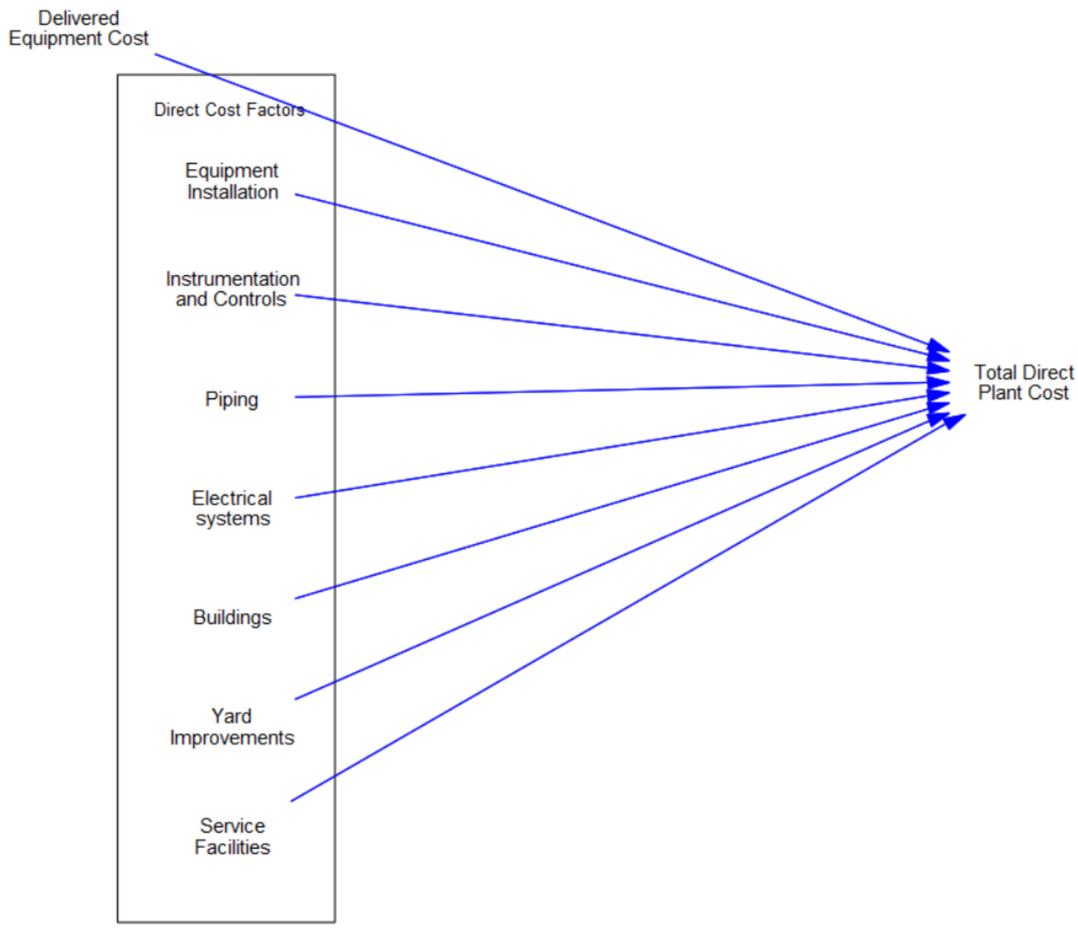

Figure 19 Generic SD Direct Cost

Utilizing the factor approach, the equation for direct cost is:

$$\text{Total Direct Plant Cost} = \text{Delivered Equipment Cost} \times (\text{Buildings} + \text{Electrical systems} + \text{Equipment Installation} + \text{Instrumentation and Controls} + \text{Piping} + \text{Service Facilities} + \text{Yard Improvements})$$

Similarly, the indirect capital costs can be developed from a range of factors and equipment costs. Some factors are also provided by Peters et al. (Peters et al., 2003) and the equation for indirect costs is very similar to the direct cost calculation.

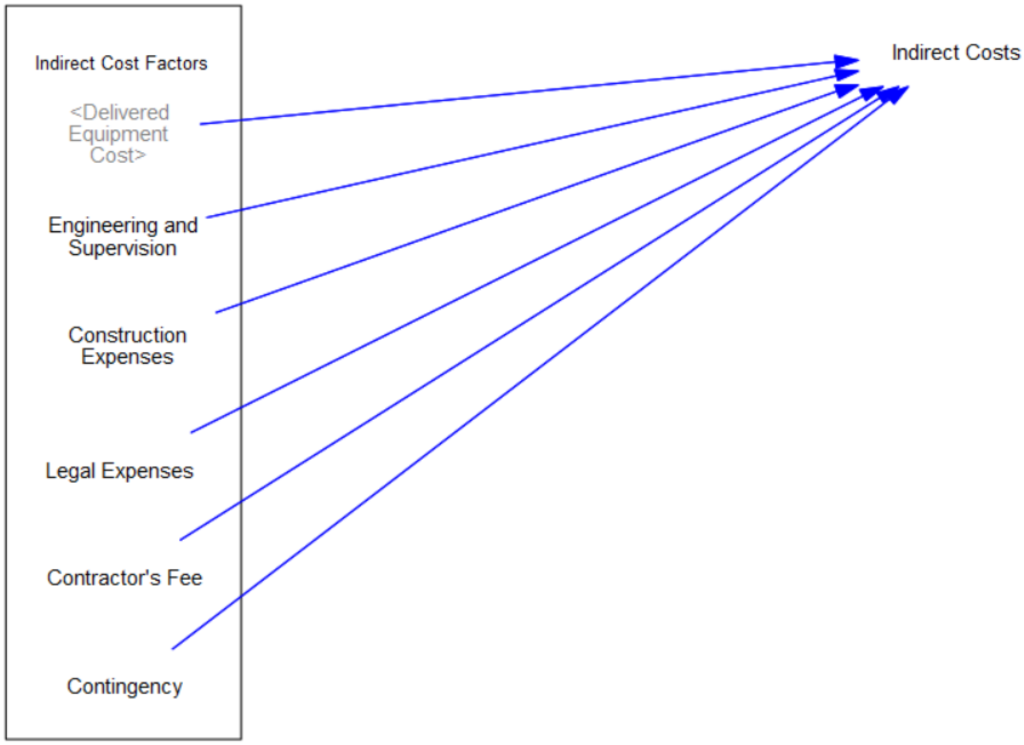

Figure 20 Generic SD Indirect Costs

Indirect Costs = Delivered Equipment Cost×(Construction Expenses+ Contingency+ Contractor's Fee+ Delivered Equipment Cost+ Engineering and Supervision+ Legal Expenses)

While these equations are simple, they afford flexibility for evaluating the two main components of capital costs. Costs that are well known or determined via other means can be used while costs that are not yet determined or understood can be estimated via the factor approach.

The combination of the direct and indirect costs as well as the addition of working capital is the total capital cost in this simple approach.

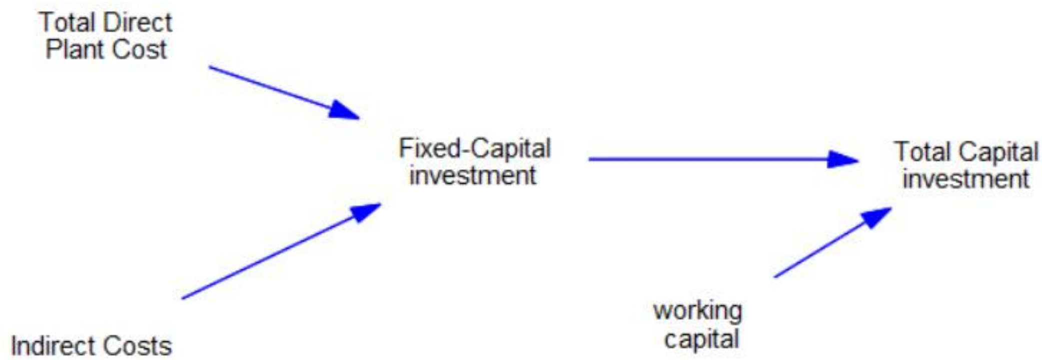

Figure 21 Generic SD Total Capital Investment

As with the other estimates the working capital can be estimated as a factor of the fixed capital which in addition to the fixed capital makes for the total capital investment.

Table 10 Percent of Delivered Equipment cost for Different Plant Types (Peters et al., 2003)

Peters table	Solid Processing Plant	Solid-Fluid Processing Plant	Fluid Processing Plant
Direct Cost			
Purchased Equipment Delivered	100	100	100
Purchased Equipment installed	45	39	47
Instruction and Controls (installed)	18	26	36
Piping(installed)	16	31	68
Electrical system (installed)	10	10	11
Building (included services)	25	29	18
Yard improvements	15	12	10
Service Facilities (installed)	40	55	70
Total direct plant cost	269	302	360
Indirect Cost			
Engineering and Supervision	33	32	33
Construction expense	39	34	41
legal expenses	4	4	4
Contractor's fee	17	19	22

Contingency	35	37	44
Total indirect plant cost	128	126	144
Fixed capital investment	397	428	504
Working Capital (15% of total capital investment)	70	75	89
Total Capital Investment	467	503	593

4.3 Generic Dynamic Operating Costs

As determined from the literature on TEAs, operating expenses are broken down into various categories. Some of these costs change with the operating level of the process while others are fixed and do not change with the process and also some others are just general costs that must be considered for a complete analysis of the operating costs (Burk, 2018).

The variable costs can be developed from the process flow rates from the process model and the size of the equipment. These will be the amount consumed or produced and the costs associated with that flow based on research or quotes. A common breakdown of these costs is raw materials, waste treatment, utilities, and operating labor (Burk, 2018). Additional costs that change with the scale of the process are things like supervisory labor, maintenance, supplies, royalties, and external testing which can be estimated based on factors relative to either the capital costs or other of the core variable operating costs (Peters et al., 2003; Turton et al., 2003).

Operating Costs

1. Variable costs	Relative cost		USD/y
a. Raw materials	-		$17,155,502
b. Waste treatment	-		$923,284
c. Utilities	-		$773,619
d. Operating labor	-		$720,057
e. Direct supervisory & clerical labor	0.18	x operating labor	$129,610
f. Maintenance & repairs	0.06	x fixed capital	$349,850
g. Operating supplies	0.01	x fixed capital	$52,477
h. Laboratory Charges	0.15	x operating labor	$108,009
i. Patents and royalties	0.03	x total operating cost	$778,792
Total variables costs			$20,991,201
2. Fixed costs			
a. Depreciation	-		-
b. Local taxes & insurance	0.03	x fixed capital	$174,925
c. Plant overhead costs	0.60	x (Line 1d + 1e + 1f)	$719,710
Total Fixed costs			$894,635
3. General costs			
a. Administrative costs	0.15	x (Line 1d + 1e + 1f)	$179,928
b. Distribution & marketing costs	0.10	x total operating cost	$2,595,972
c. Research & development	0.05	x total operating cost	$1,297,986
Total general costs			$4,073,886
Total operating cost less depreciation			**$25,959,722**

Figure 22 Operating Cost Breakdown for Example TEA (Burk, 2018)

Akin to some of the variable costs, the fixes, and general costs can be estimated based on factors of other costs such as capital costs or operating costs. Starting points for these factors and approaches are available in the literature (Turton et al., 2003). The dynamic model diagram for this section is increasingly complex as compared with the capital cost due to the interconnected equations of the estimates. While that may seem like a hindrance, it is a visual representation of the ease in which an error could be incorporated. The full list of equations matches that of Turton et al. as shown in Table 11.

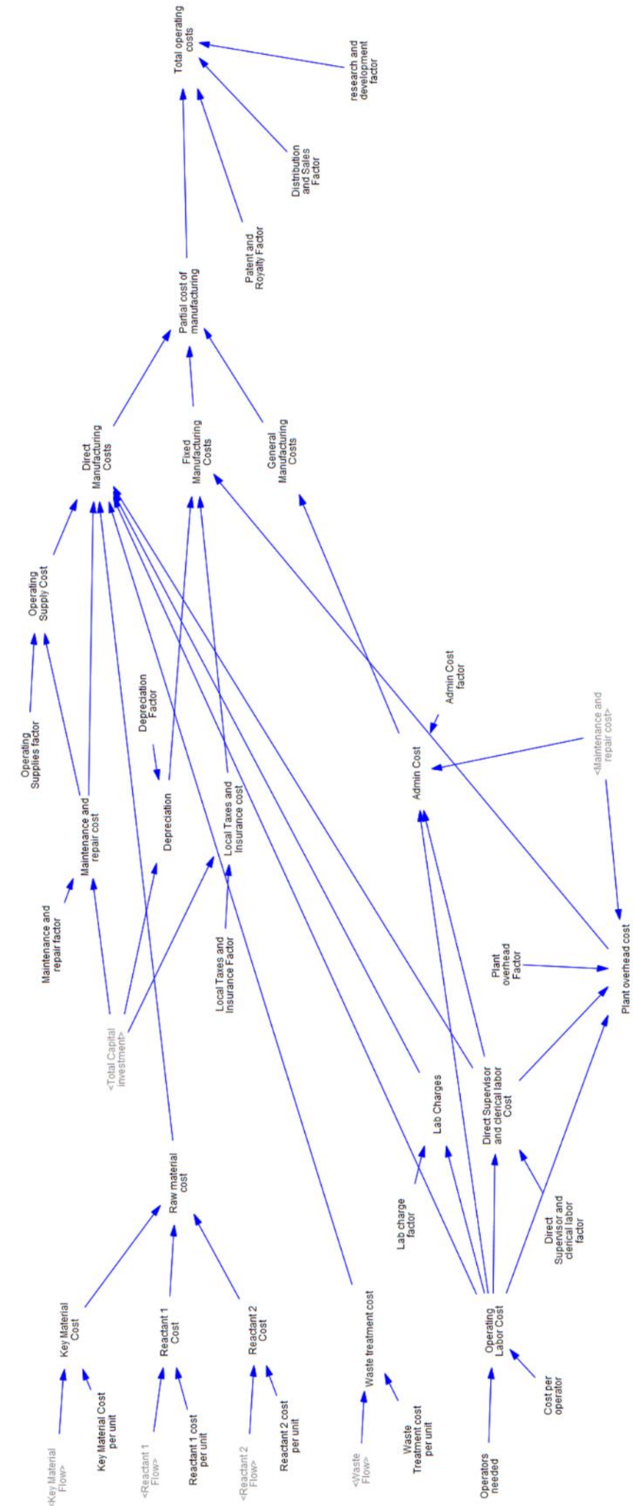

Figure 23 Generic SD Operating Costs

*Table 11 Multiplication Factors Estimating Manufacturing Cost*** **(Turton et al., 2003)**

Cost Items	Typical Range of Multiplying Factors
1. Direct manufacturing costs	
a. Raw materials	CRM*
b. Waste treatment	CWT*
c. Utilities	CUT*
d. Operating labor	COL
e. Direct supervisory and clerical labor	(0.1 - 0.25)COL.
f. Maintenance and repairs	(0.02 - 0.1)FCI
g. Operating supplies	(0.1 - 0.2)(Line 1.F.)
h. Laboratory charges	(0.1 - 0.2) C(L
i. Patents and royalties	(0 - 0.06)COM
Total direct manufacturing costs	CRM + CWT + CUT + 1.33COL +0.03COM+0.069FCI
2. Fixed manufacturing costs	
a. Depreciation	0.1FCI***
b. Local taxes and insurance	(0.014 - 0.05)FCI
c. Plant overhead costs	(0.50 - 0.7)(Line 1.D. + Line 1.E. + Line 1.F.)
Total fixed manufacturing costs	0.708COL + 0.068FCI + depreciation
3. General manufacturing expenses	
a. Administration costs	0.15(Line 1.D. + Line 1.E.+ Line 1.F.)
b. Distribution and selling costs	(0.02 - 0.2)COM
c. Research and development	0.05COM
Total general manufacturing costs	0.177COL + 0.009FCI + 0.16COM
TOTAL COSTS	CRM + CWT + CUT + 2.215COL + 0.190COM + 0.146FCI + depreciation
*Costs are evaluated from information given on the PFD and the unit cost	
**Costs are given in dollars per unit time (usually per year)	
***Depreciation costs are covered separately in Chapter 7. The use of 10% of FCI is a crude approximation at best	

One area where the dynamic modeling approach identifies a question relative to the factor approach is in the units. Typically, factors can be treated as dimensionless as they are multiple of some quantity, and they maintain the units. It is noted in Turton et al.

that the identified costs of manufacturing are in the units of dollars per unit time, that time typically being a year. In many cases, the factor is indeed a dimensionless multiple of a parameter that is considered in dollars per time, such as direct and supervisor labor which is a factor based on operating labor. However, in the case of Maintenance and Repairs the factor is multiplied by the fixed capital which will have units of dollars, and thus the factor must include a time element. This is easily identified within the dynamic model by checking the units but is not immediately clear from the straight factor approach. This confusion is continued when other factors are multiplied by the maintenance and repair cost such as in the case of operating supplies.

4.4 Generic Dynamic Income

Like the concept of operating costs, a method to estimate the income of a process is the rate of products produced multiplied by the price of that product. As observed in the literature a common approach is to use an average price from the past as the representative price of products. For novel products an estimate of the price that the product commands may need to be estimated based on experience.

Other projects and processes do not make a product but instead result in some savings which can be represented as a comparison of the overall costs of the process relative to the standard or estimated nominal case (Turton et al., 2003).

In this generic form of the TEA, the product rate multiplied by the product unit price formulation is used for product income.

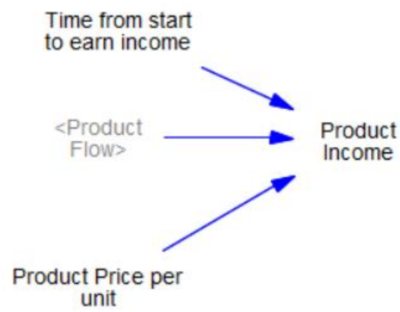

Figure 24 Generic SD Income

Although one of the main elements that change the outcome of a TEA, the income portion of standard TEAs is one of the simplest elements of the TEA.

4.5 Generic Dynamic Economic Metrics

Economic metrics come in many forms and which ones are relevant depends on how the TEA is being compared to other investments and alternatives as they must provide outputs that are comparable to each other.

4.5.1 Generic Dynamic Revenue, Costs, and Profit

Simple analyses of the economic metrics of a project or process can be the revenue, the cost, and/or the profit of the project. The revenue can be determined from the income from the process and based on that income the profit is from the revenue minus the operating costs and annualized operating costs. These parameters can be calculated easily from the previously mentioned costs and incomes.

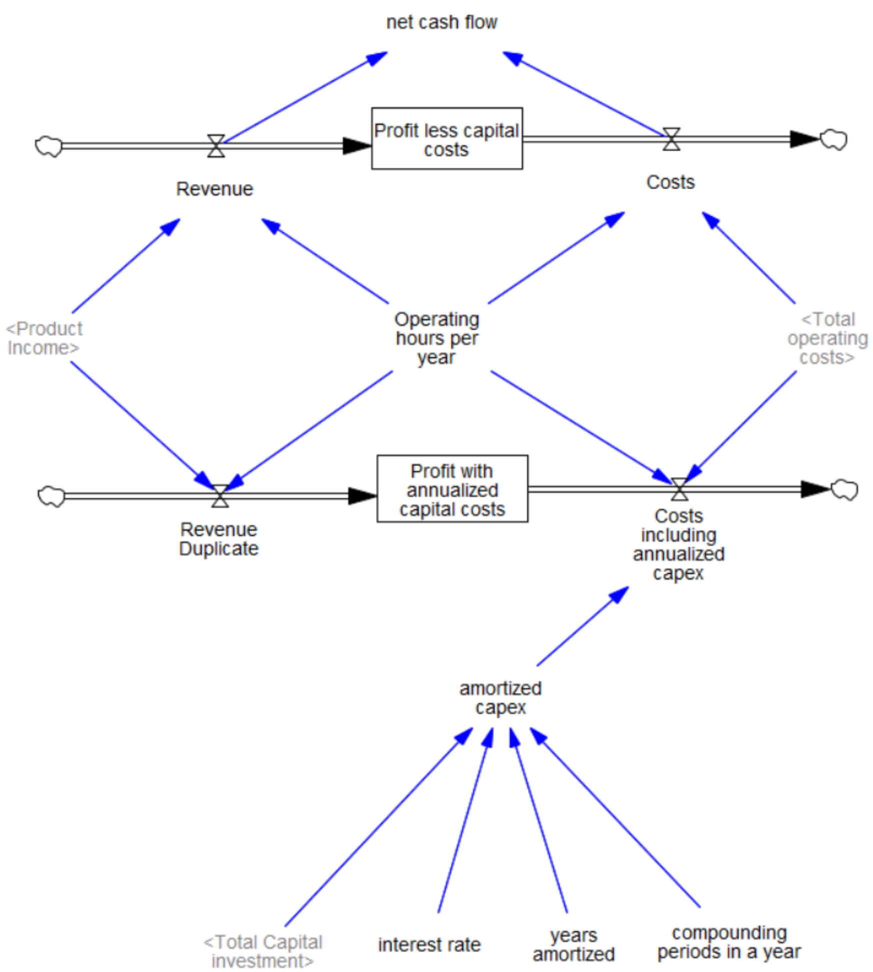

Figure 25 Generic SD Revenue and Profit

As stated, depending on the comparison metrics, profit can be calculated with or without the capital expenditure amortized, or as shown both ways for easy comparison to multiple potential different options. In this case, the profit is treated as an accumulation over the entire lifetime of the project where the only removal of profit is via operating costs and or amortized capital costs. There will be draws on the profit for other projects or needs but for comparison purposes, the accumulation approach has been assumed.

4.5.2 Generic Dynamic NPV, IRR, Payback Period

Using the revenue, costs, and profits additional economic analysis is conducted. The commonly used metrics from the literature are net present value, internal rate of return, and payback period. The calculation of these metrics is straightforward but does depend on several assumptions that must be clear to properly compare these metrics.

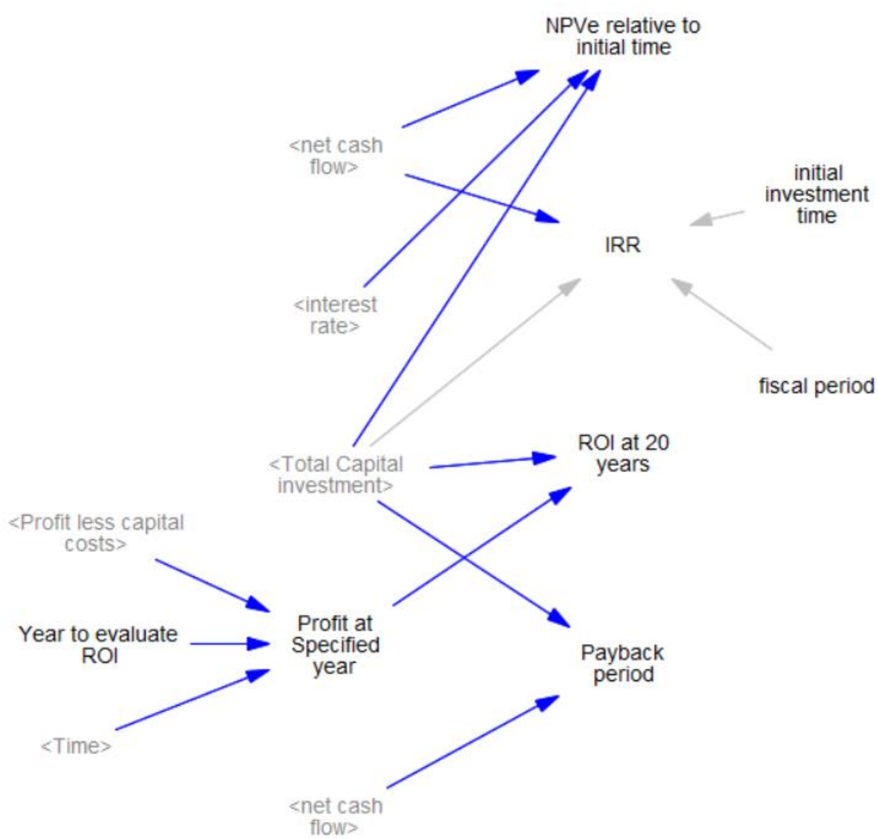

Figure 26 Generic SD NPV, IRR, Payback Period

Several built in functions exist in Vensim exist for the purpose of economic analysis, especially to compare with spreadsheet-based calculation methods. The net present value function is equivalent to how the net present value is calculated in spreadsheet software. In addition to the NPV function, there is an internal rate of return function that can be used to develop the IRR for the project. Other metrics are calculated using various economic parameters such as profit, CAPEX, and net cash flow. The return on investment can be calculated based on the accumulated profit as of a specified time relative to the capital costs(Fernando, 2022). Finally, the payback period can be calculated from the investment and the net cash flow (Kagan, 2022).

4.6 Generic Dynamic Sensitivity Testing

Sensitivity testing is used to evaluate the effect on the overall outcome of the process from changes in input parameters. The range used can be determined from historical ranges or experiences as noted in the literature and the result can identify areas that are risks or opportunities. Using the capabilities built into the system dynamics tool set detailed sensitivity analysis can be performed. With a simple range applied to all of the parameters, a plot of the likelihood of various outcomes can be made as is shown below for IRR for the generic process.

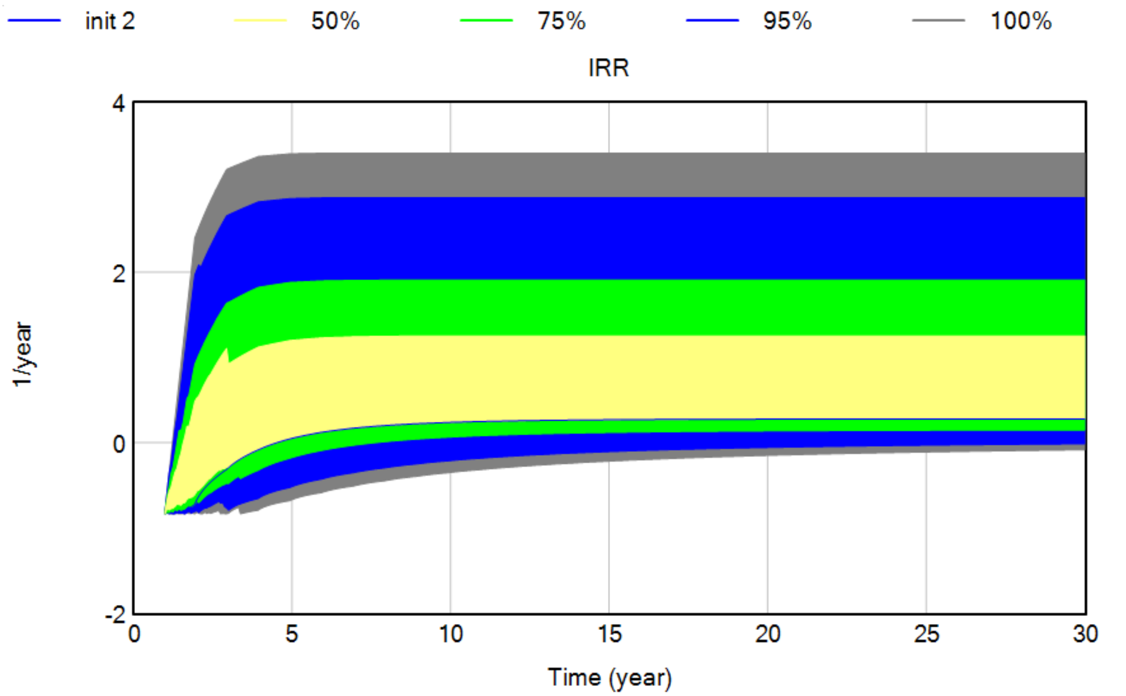

Figure 27 Generic SD Sensitivity Plot

This plot was developed using a Random uniform distribution across the range defined for all of the potential variable elements in the model. The full table can be found in Appendix A.

4.7 Generic Dynamic User Interface

As the complexity of the model increases, efforts to maintain its understandability include separating variables across different pages of the model to categorize calculations by their type but this also makes it more challenging to interact with the model. As exemplified in the management flight simulator research a dashboard or user interface with key decision variables and key outputs allows users to interact with the model without having to go specifically to various constants to change values and then go to the desired outlet variables and observe the changes. In this template case, a simple user interface can take the following form where the process parameters, financial parameters, and key economic metrics are available to be changed and the result observed from one area of the model.

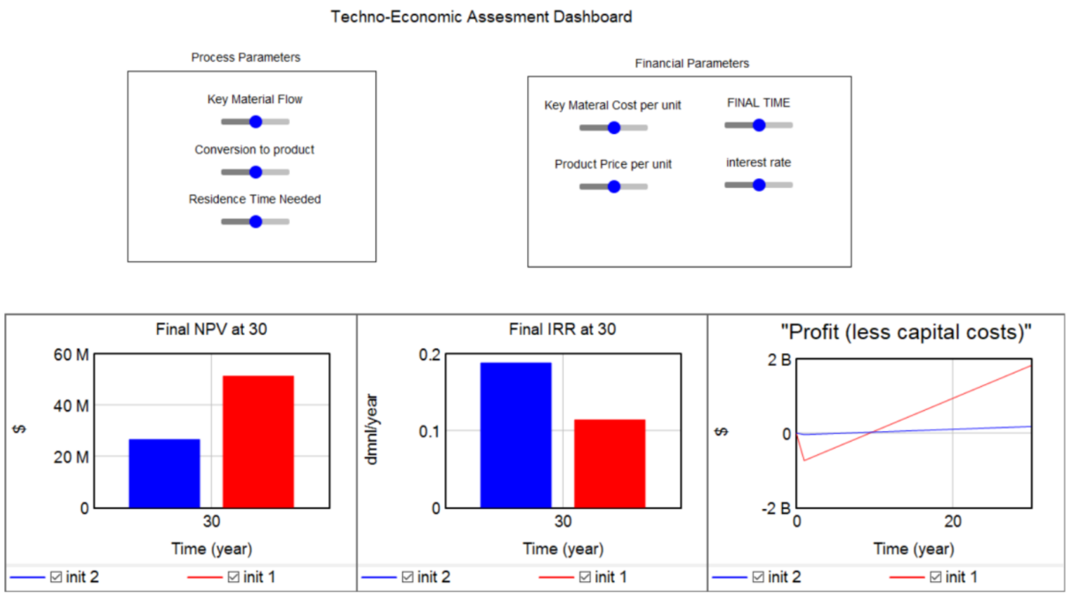

Figure 28 Generic SD Dashboard UI

Additional variables can be added as well as results displayed as deemed relevant by the model designers.

4.8 Summary

A generic dynamic TEA has been constructed to match the elements that are commonly used in spreadsheet TEAs and the added benefits of the system dynamics modeling approach such as sensitivity analysis are incorporated as well. This builds on the elements of TEAs included in other system dynamics research in a more integrated manner. The documented version of the model can be found in Appendix B.

CHAPTER 5

5 ADDITIONAL ELEMENTS RELEVANT TO TECHNO-ECONOMIC ASSESSMENT IN SYSTEM DYNAMICS

System dynamics literature has many examples of applications that are relevant to the type of analysis that is needed in a TEA. The application of several of those elements, namely project modeling, pricing modeling, and hiring modeling, to the form and content of a TEA allows for the eventual integration of those modeling examples into the dynamic TEA framework.

5.1 Project Model Applied to TEA

An analysis of the design, engineering, and construction aspects of TEAs can be done with the identified project model. The ranges of the following parameters are stated as to be picked based on engineering judgment:

- Design and engineering factor
- Factors that lead to total direct cost
    - Mechanical equipment
    - Building costs
    - Civil costs
    - Installation costs
    - Lagging and painting cost
    - Piping, plate work, duct work costs
    - Site electric and controls cost

    - Sitework and landscaping costs
- From Peters et al.
    - Table of range of costs that make up fixed capital investment
- Approach
    - Assume a purchased equipment cost
    - Calc the project costs from low- and high-end ranges
    - Use the low-end ranges and common values from project models (below) to see where they land relative to the high range
    - See how large the high range would be using the project model
    - Sensitivity analysis with the ranges?

The collection of costs associated with the execution of the project, as noted in Peters et al., for "multipurpose plants or large additions to existing facilities" are as follows:

Table 12 Direct and Indirect factors of FCI (Peters et al., 2003)

Category	Component of cost	Low % of FCI	High % of FCI
Direct Cost	Equipment installation	6	14
	Installed instruments and controls	2	12
	Piping installed	4	17
	Electrical systems installed	2	10
	Buildings including services	2	18
	Yard improvements	2	5
	Service facilities installed	8	30
Indirect Cost	Engineering and supervision	4	20
	Construction expenses	4	17

	Legal expenses	2	3
	Contingency	5	15

One element to be considered is the direct costs, the ranges provided include both the equipment needed for that component as well as the labor costs to install that equipment. The factor for labor as a fraction of total project cost of 30% to 40% has been used in several references for commercial projects (Artono, 2021; McKay, 2018; Sullivan, 2019). This factor can be corroborated by comparing the values for purchased equipment and the installation costs for purchased equipment by Peters et al.

Table 13 Comparison of FCI factors and Other Sources

Purchased Equipment	Purchased equipment installation	Installation/Equipment
15% of FCI	6% of FCI	40%
40% of FCI	14% of FCI	35%

Using this ratio for labor cost to total project cost with the provided fractions of FCI of various labor and an example case of $100,000 of fixed capital, the labor costs of the project can be calculated. The labor costs are relevant as the project model is a model of people's effort needed to complete a project which is measured in person-hours or person-months and thus only includes labor costs. Using the simplest approach, a 30% factor on total project costs, allows for an estimate of the labor needed for the project based on an assumed labor burden rate and working hours per year. These labor and an estimate of the planned project duration imply productivity that is used as the nominal productivity for the project. The labor also initializes the staffing parameters. The error fraction is initialized at 15% but allowed to vary with the error on errors feedback loop.

The final average error fraction observed is 35% which is similar to the error fraction of 33% observed in previous examples of projects examined in the literature (Reichelt & Lyneis, 1999). With the project model, an estimated actual labor cost can be obtained which when added to the assumed nonlabor 70% of the total cost estimate provides a new total cost for the project. A plot of how these costs accumulate over time shows when the project will meet its estimated cost and what the final total cost may be with the starting point of all of the low end of the percent of FCI parameters.

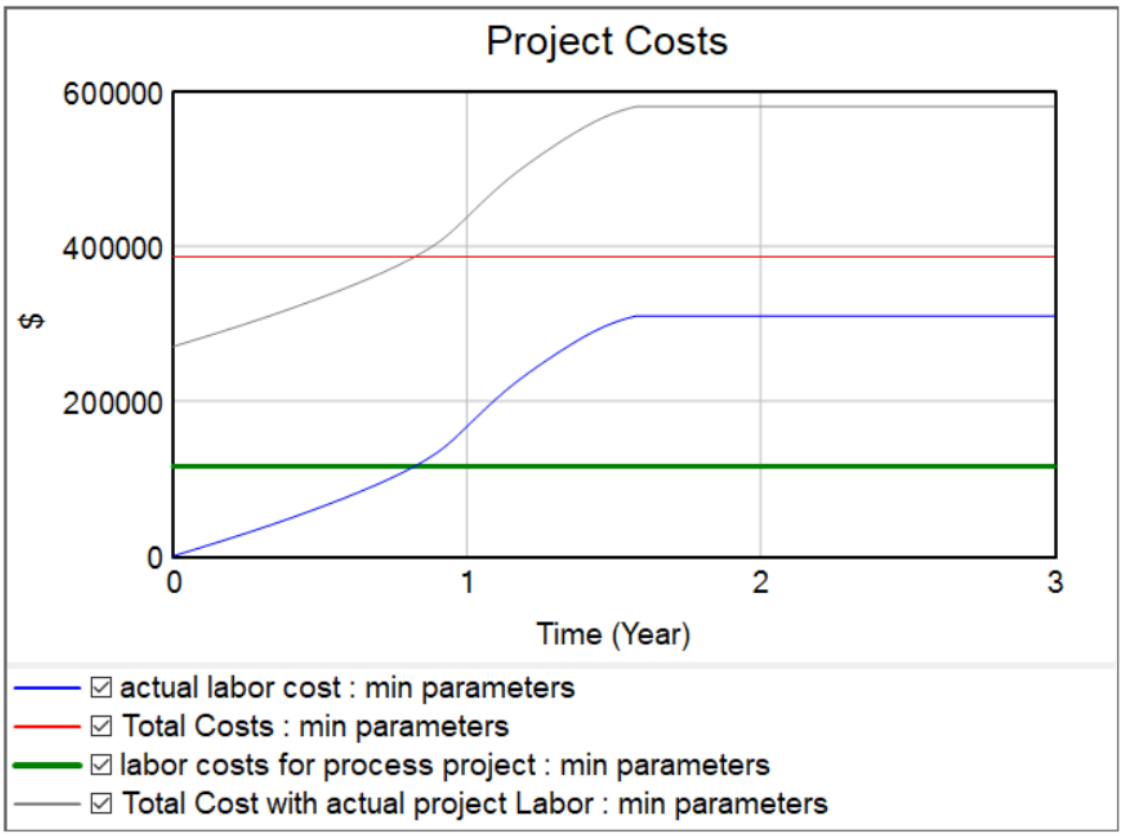

Figure 29 Project Cost Estimates

The result is a project implementation cost that is 1.5 times the estimated cost, based on the low-end parameters. A logical assumption is then to compare that to using the high end of the FCI parameter range. For the same purchased equipment cost of $100,000, the total project cost using the high-end range without considering the project model changes is $597,500, which is near to the project cost with actual labor of $581,000 using the low end of the FCI range for the cost parameters.

Table 14 Table of Labor cost and Project Cost for FCI Ranges and Project Effects

Range of FCI Parameter Used	Project Effects Considered	Total Labor Cost Estimate	Total Project Cost Estimate
Low	No	$116,000	$387,000
Low	Yes	$310,000	$581,000
High	No	$179,000	$597,500

While the high range does generally agree with the low range with project effects considered, it is notable that the cost distribution between those two cases is not the same. The project effects case with the low end FCI parameters still has a higher labor cost than even the high end FCI parameters 1.7 times. This may be relevant if there are different considerations for labor spending rather than additional capital equipment expenditures.

5.2 Adapted Pricing Model to REE

Parameterizing the commodity pricing model for rare earth elements allows for a dynamic pricing approach to estimate how the price of the rare earth elements may change over the long-time span that is planned in TEAs. This approach attempts to add the value of prior attempts at adding a dynamic pricing element to TEAs but in a way that is easily integrated with all other aspects of the model (Deng et al., 2021). Both Glöser-Chahoud et al. and Deng et al. found that the demand increase is driven by GDP growth. Similarly, both articles observed a cyclical nature of the supply side in the rare earth industry as well as the copper industry. As the work of the Glöser-Chahoud et al. was conducted in 2016, it is possible to compare their modeled future copper price with data. While the model does not match perfectly it does provide a dynamic that is similar to the price on a 2015 USD basis (*Consumer Price Index Data from 1913 to 2023 | US Inflation Calculator*, 2008; Nasdaq, 2023).

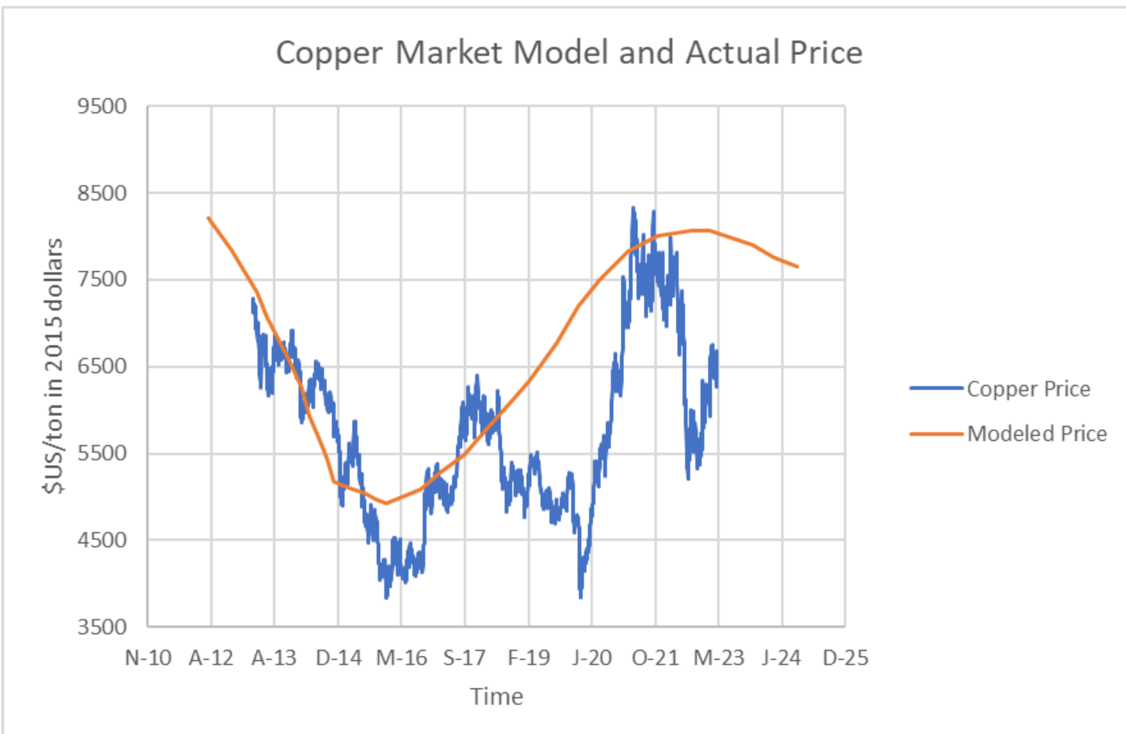

Figure 30 Copper Price Model Comparison

Applying these lessons to the Glöser-Chahoud et al. required the definition of several model variables and calibration to historical data to evaluate its applicability to estimate future prices.

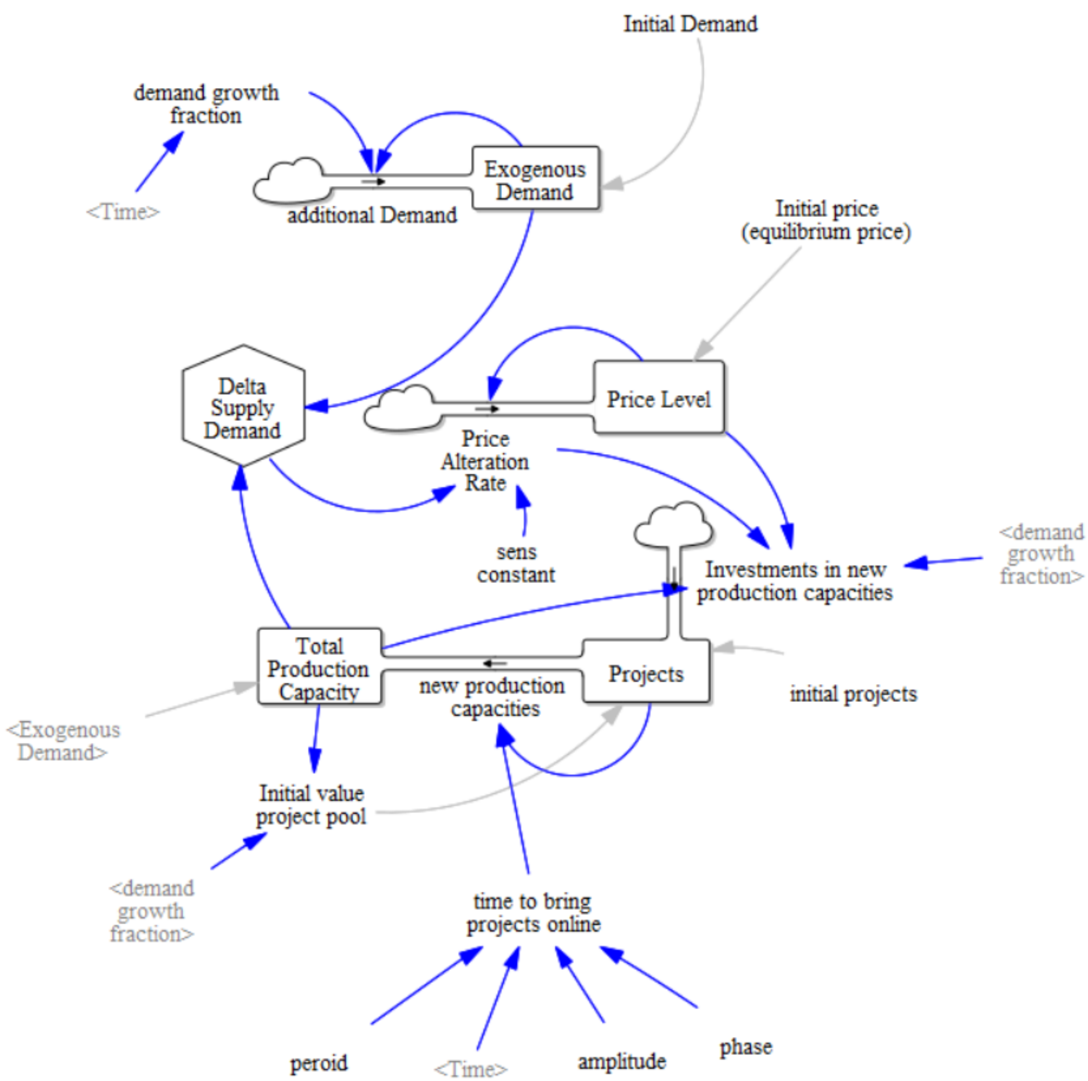

Figure 31 Adaptation of Copper Price Model Adapted from (Glöser-Chahoud et al., 2016).

The timeframe chosen for calibration is starting in the year 1980 through to 2015. Historical data for demand (consumption), production capacity and REE price is available for the date range (Kelly & Matos, 2014). These data allow for several areas of parameter estimation of a price sensitivity constant and the nature of the time delay for production projects to come online as well as an estimate of the demand growth rate for that time period. The sensitivity constant and demand growth rate are constants that are adjusted to align the simulation with the data. The structure of the time delay for production projects to start producing uses prior work in both copper and REE that observed a cyclic variation of the rate at which production capacity comes into being (Deng et al., 2021; Glöser-Chahoud et al., 2016). The approach used with copper capacity delay was a distribution of delay times that resulted in a varying cycle of times ranging from 2 years to 6 years (Glöser-Chahoud et al., 2016). As a simplification to that approach a sine wave with a varying period, amplitude, and phase has been used to provide a calibratable cyclically varying time for projects to start producing REE. In addition to the trends of demand, production capacity, and price, the price for 1980 is assumed to be the equilibrium starting price and production capacity and demand are equal at the start of the simulation.

The results for demand and price relativity to their historical counterparts show a general agreement with the data and the simulation. This is not intended to perfectly predict REE prices but instead to capture the general change over time such that a more realistic range of prices can be applied in the dynamic TEA rather than a static price. In this light, the price spike of the 2010s is not replicated by the date specifically but the general trend of an increase and decrease is captured by the model.

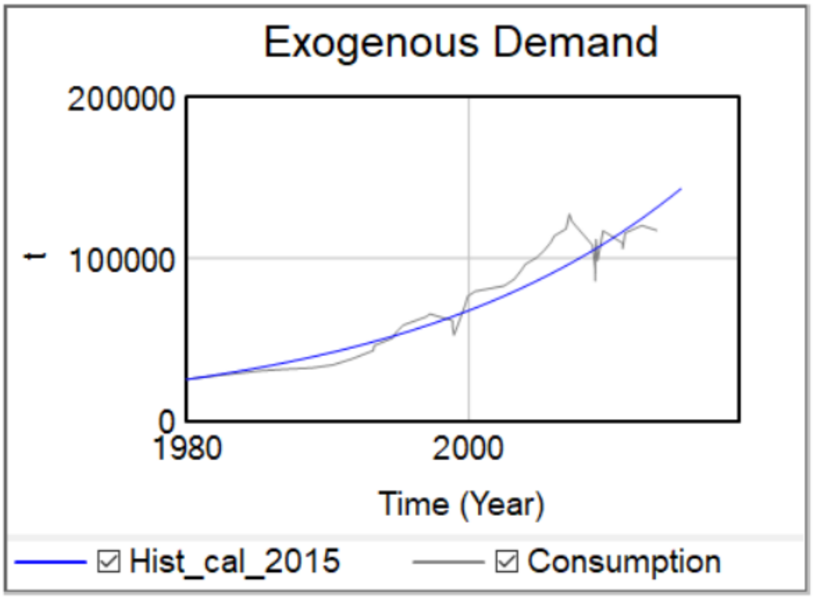

Figure 32 Rare Earth Demand and Modeled Demand

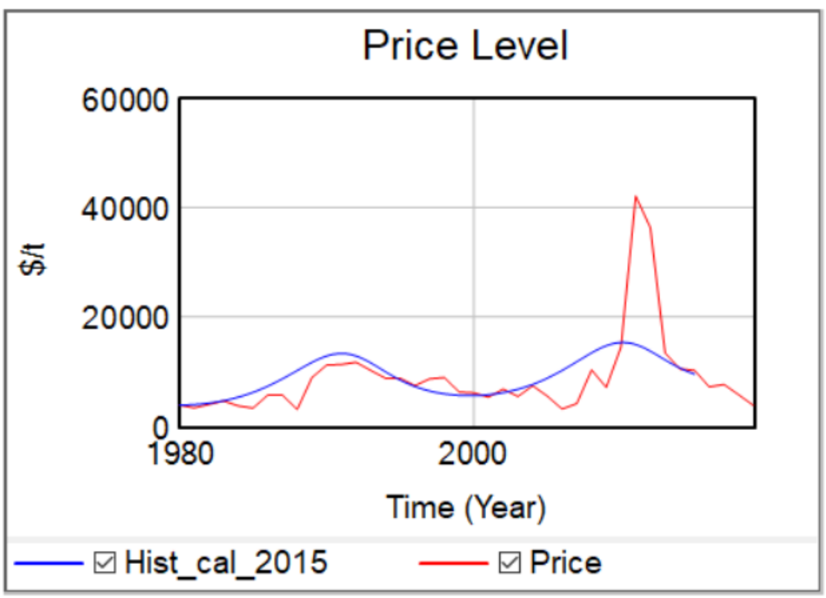

Figure 33 Rare Earth Price and Modeled Price

Looking forward in time, the demand for REE is assumed to be exogenous and driven by GDP growth as was observed for copper and REE (Deng et al., 2021; Glöser-Chahoud et al., 2016). Using the results from Deng et al. as the prediction for GDP growth from 2019 forward, the simulation produces a price forecast for REE that varies over time and captures similar highs and lows seen historically.

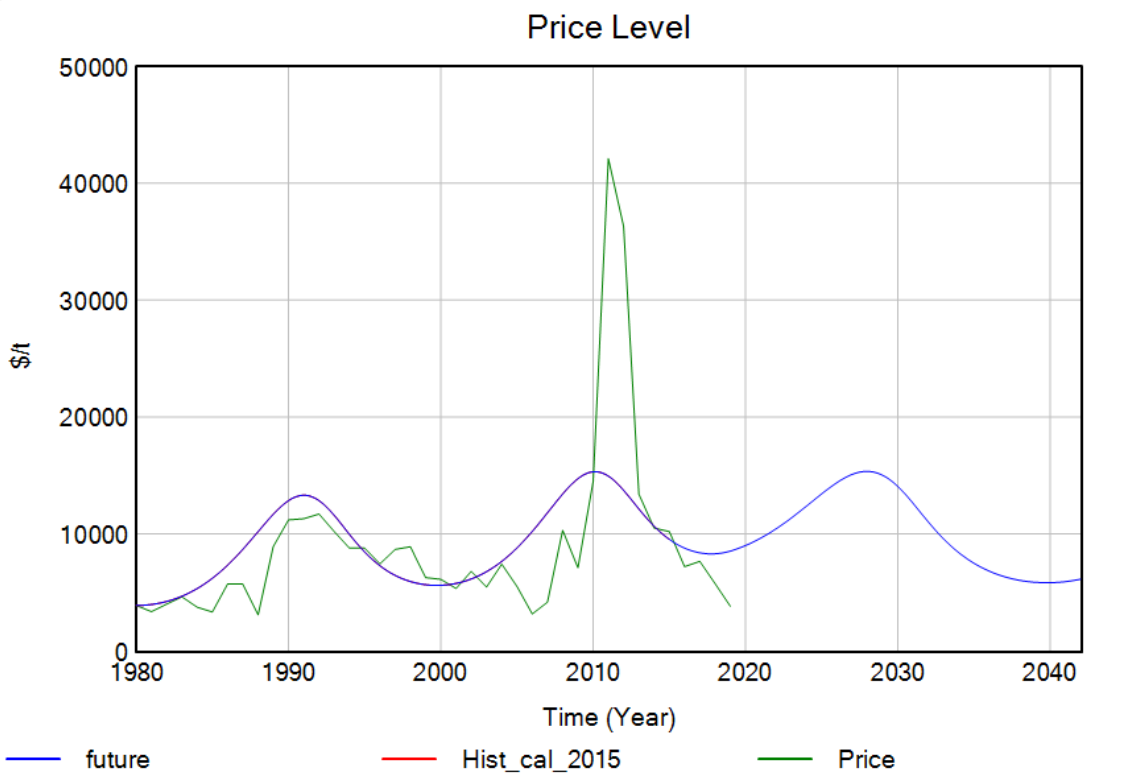

Figure 34 Comparison of Historian Price Level with Model Including Future Predictions

This model approach can use the above scenario as the base case price for the REE TEAs and can apply a variation to the expected growth rate of demand to evaluate the range of future prices that may be possible. The changes following the price spike of 2010 are not inherently considered within this dynamic pricing model though so the future price potential may be more uncertain.

This does not consider the market price differences for products as Deng et al. discusses or the challenges of market size for various REE products and how the production volume of specific REEs may impact the overall price due to the amount supplied from a process and the typical market capacity. As noted by Mann, there may be chances for new product growth based on an additional availability of supply of certain elements (Mann, 2021). This approach also does not consider the difference between rare earth elements which can be large in terms of price and market size. For example, prices range from $2 per kg for Cerium to $4600 per kg for Scandium. Considerations of this nature will be required for more reasonable pricing dynamics of rare earths. One additional caution is regarding the accuracy of market pricing models which can depend on many exogenous factors that if not considered may reduce the likelihood of the model matching future prices.

5.3 Hiring Model Conversion to New Processes

Applying some of the changes to convert the standard hiring model to one more applicable to the needs of a TEA required the adjustment of the types of stocks being used, specifically looking at how many candidates in addition to the actual employees. A mechanism to drive hiring based on the expected labor need from the OPEX model sets the recruiting rate which through a series of stocks and flows results in experienced personnel working on the process. This approach accounts for the time it takes to recruit, vet, and hire candidates, and to train new employees.

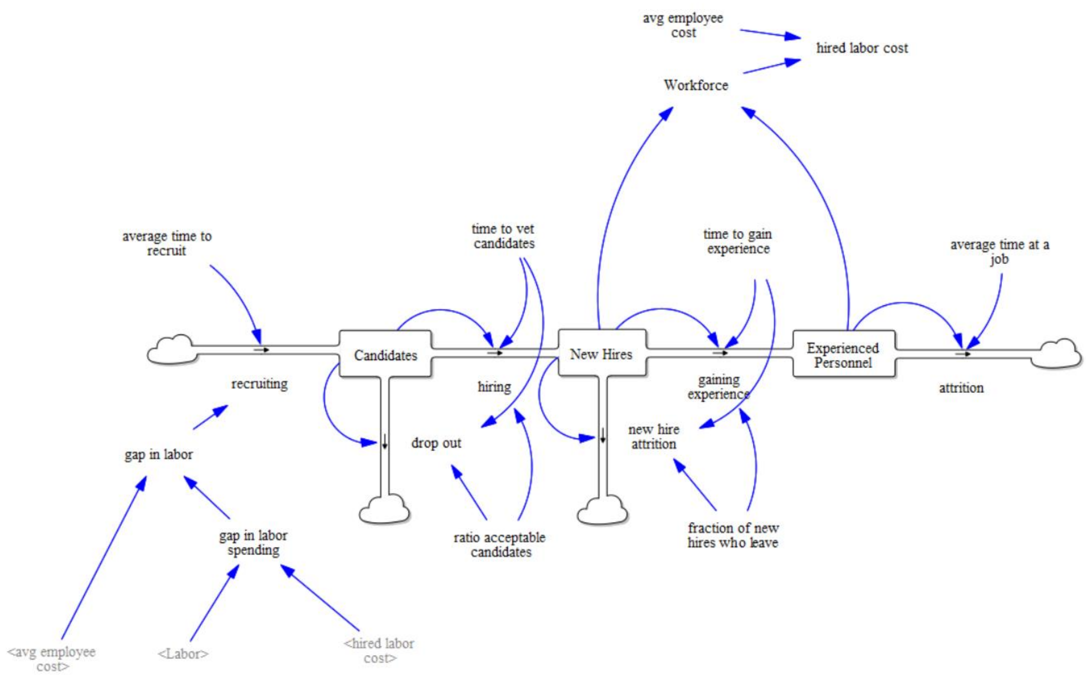

Figure 35 Applied Hiring Model

Including this additional modeling for the labor provides multiple benefits for ensuring the reality of the TEA that labor is needed to create revenue and that experienced labor requires an intentional effort over time to develop to a level that can make a process functional.

5.4 Summary

Modifications of various models that are relevant but not included in standard TEAs have been conducted. A simple project model was parameterized for the type of information typically available in TEAs. An alternative approach to pricing changes was applied to the rare earth market based on demand growth and the rate of production growth rather than simply fitting past data (Deng et al., 2021). In order to support the staffing needs of novel processes a standard hiring change model was modified to capture the process and needs relevant to a TEA.

CHAPTER 6

6 ERROR IDENTIFICAITON IN TECNO-ECONOMIC ASSEMENTS

Errors in TEAs may drive alternative conclusions regarding the technical or economic feasibility of the processing being analyzed. An evaluation of how the lessons from spreadsheet research can apply to TEAs makes a case for the potential for errors to exist in spreadsheet-based TEAs. An application of the generic dynamic model to an existing TEA for the rare earth extraction process attempts to discover any errors and the methods by with they are discovered.

6.1 How Spreadsheet Error Research Relates to TEA

As observed in the literature it is common to use spreadsheet software for the development of TEAs. These analyses vary in complexity based on the project complexity. The following collection of spreadsheet-based TEAs shows the range of complexity in the number of sheets and calculations used. By applying the low end cell error rate of 1.1% for experienced graduate developers and the high end cell error rate of 9.7% for experienced developers as summarized by (Panko, 2008a) a potential range of the number of cells with errors can be estimated.

Table 15 Application of CER Rates to Spreadsheet TEAs

		Potential Cells with Errors	
Topic	Calculations	CER=1.1%	CER =9.7%
Consumer Product(Burk & Zotter, 2021)	107	1	10
Pharmaceuticals (Burk & Zotter, 2021)	362	4	35
Food Product (Ellersick, 2021)	893	10	87

Chemical Product (Burk & Zotter, 2021)	438	5	42
Rare Earth Product (Laudal, 2017)	2688	30	261
Rare Earth Product*	2335	26	226
Demonstration Plant*	6830	75	663
Rare Earth Product*	6978	77	677

*Confidential from UND REE Project

This estimate is at a very rough level, but it does help to understand what kind of validation should be thought about and what kind of test may be appropriate for these models. It is not clear from the research what types of errors are likely which then implies detailed testing and auditing would be needed to validate the sheet completely. It is also not clear what testing was done before publishing these models, but several aspects of the recommended practices can be evaluated, specifically around documentation and readability.

Table 16 Documentation and Readability of Spreadsheet TEAs

Topic	Sheets	Documentation Used	Readability
Consumer Product(Burk & Zotter, 2021)	2	Basic Model Info Sheet and model approach	Named Cells in some formula
Pharmaceuticals (Burk & Zotter, 2021)	9	Orientation sheet including model approach and use notes	Some Named ranges and cells
Food Product (Ellersick, 2021)	2	None	
Chemical Product (Burk & Zotter, 2021)	9	Model info, assumptions for CAPEX, OPEX, and model structure	Some Named ranges and cells (for units)
Rare Earth Product (Laudal, 2017)	8	None in the document	Some named ranges
Rare Earth Product*	8	None in the document	Some named ranges
Demonstration Plant*	26	None in the document	Some named ranges
Rare Earth Product*	31	Sheet with guidance for user	Some named ranges

Some documentation was used in a portion of the evaluated TEAs. The level of detail depended on the project but there were cases where no specific documentation was within the document. Others had guidance on usage which will likely reduce the potential for qualitative errors due to misuse of the model.

6.2 Error Identification using SD

A dynamic model of the process is useful for exploring changes to aspects of the process that are interconnected and time dependent. In the case of TEAs, much is assumed to be constant over time, especially around process parameters. As a demonstration of modeling a process in detail and its subsequent process economics, an early TEA of the lignite extraction process was evaluated dynamically (Laudal, 2017). The process modeling aspect of this effort is much more detailed than explored in the template model as the purpose is to validate the technical parameters of the TEA for any unintentional errors.

6.2.1 Overview of this TEA

The TEA's goal was to provide a technical and economic analysis of the rare earth concentration technology which would allow for validating the commercial prospect of the developed process on North Dakota coal. A conceptual process was developed based on the lab scale testing and results. This process allowed for an evaluation of the capital and operating costs and potential revenues on a commercial scale. The result of this process is the following table of revenues and costs.

Table 17 Early REE TEA Economic Parameters

		TEA Parameters
Item	Detail	$/year
OPEX	Coal Cost	$ 525,000
	Electricity, NG, Maintenance	$ 2,300,000
	Steam	$ 47,914
	water	$ 51,626
	Operator Labor	$ 400,000
	Acid Cost	$ 493,806
	REE + Ge and Ga Processing	$ 244,608
	Base Metal Processing	$ 23,842
	15% Misc. increase	$ 613,019
	Total	$ 4,699,815
Revenue	Activate Carbon	$ 10,430,000
	Syngas	$ 799,092
	REE and Metal	$ 3,291,228
	Total	$ 14,520,320
Net Revenue	Revenue - OPEX	$ 9,820,505

6.2.2 Process Model Error Identification

Dynamic models should be grounded in reality such that as changes are made to the input parameters the outputs change appropriately and no variable components of the model are static without that making sense from a conceptual perspective (Warren, 2010). Such a rigorous model can be developed through an iterative process where additional complexity and interconnection are added as it makes sense to achieve the goal of the model. The initial attempt to capture the commercial process from the TEA used static flows as given by the process flow diagrams, mass balance, and economic analysis. Several levels of aggregation are done relative to the process design to maintain simplicity without significantly reducing the accuracy of the model. Specifically, the activated carbon process and iron separation process have been simplified to capture just the necessary elements of those unit operations. The simplified structure of the process is shown below.

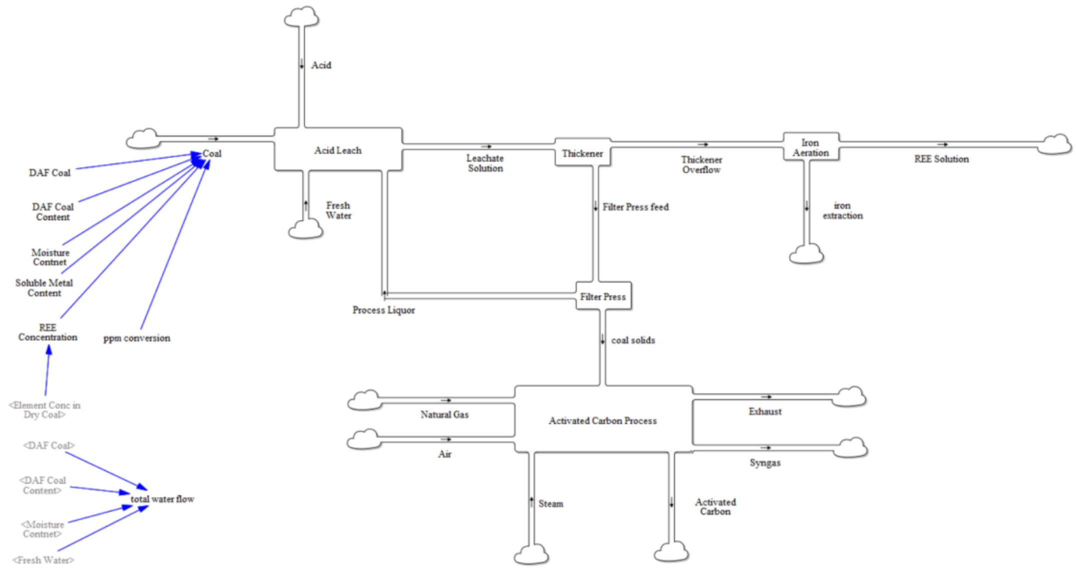

Figure 36 Early REE Process Model Diagram

Quick checks can be done to validate the functionality of the model. One is the mass balance and for the process, as defined in the TEA, this can be done by looking at the levels of the stocks. As this model is a steady state process what mass comes in should come out and there should be no accumulation in the process over the simulation time (one operating year). Analysis in this manner confirms both accumulation and depletion of stocks that would result in overflowing or empty unit operations if the process operated in this manner. In some cases, it is a small amount of material considering the time scale of a year but in others it is not insignificant.

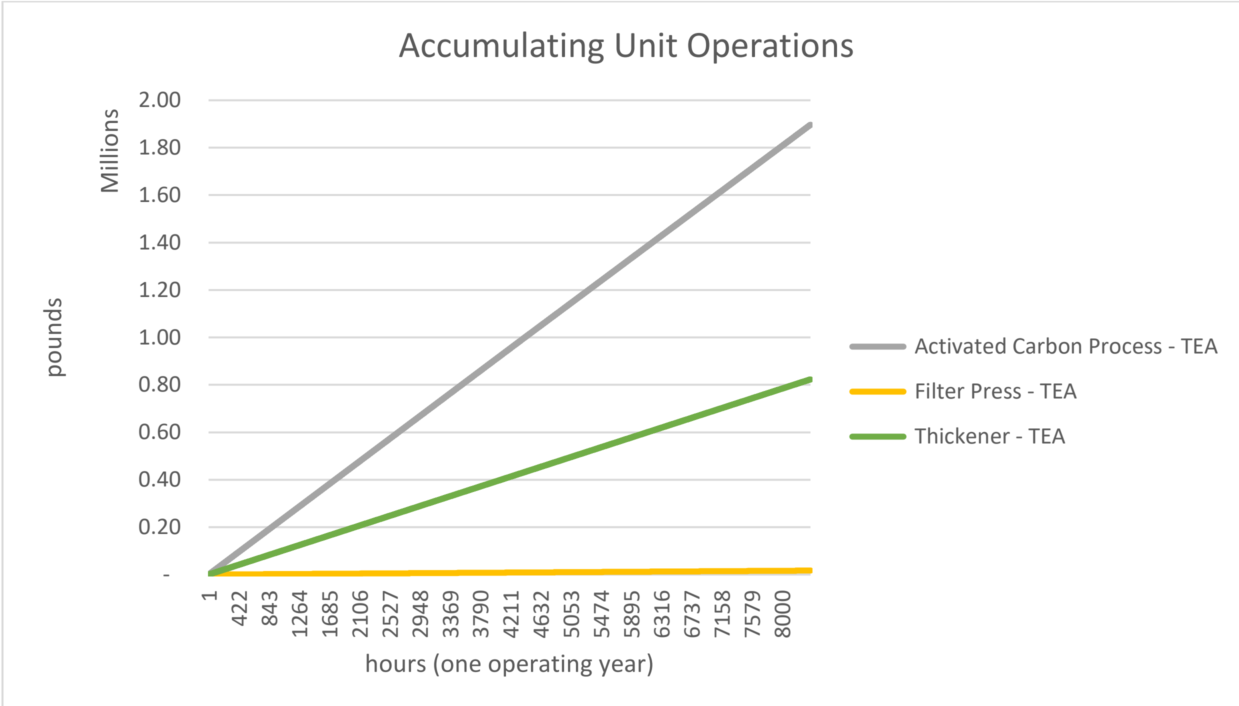

Figure 37 Process Unit Operations that are Accumulating

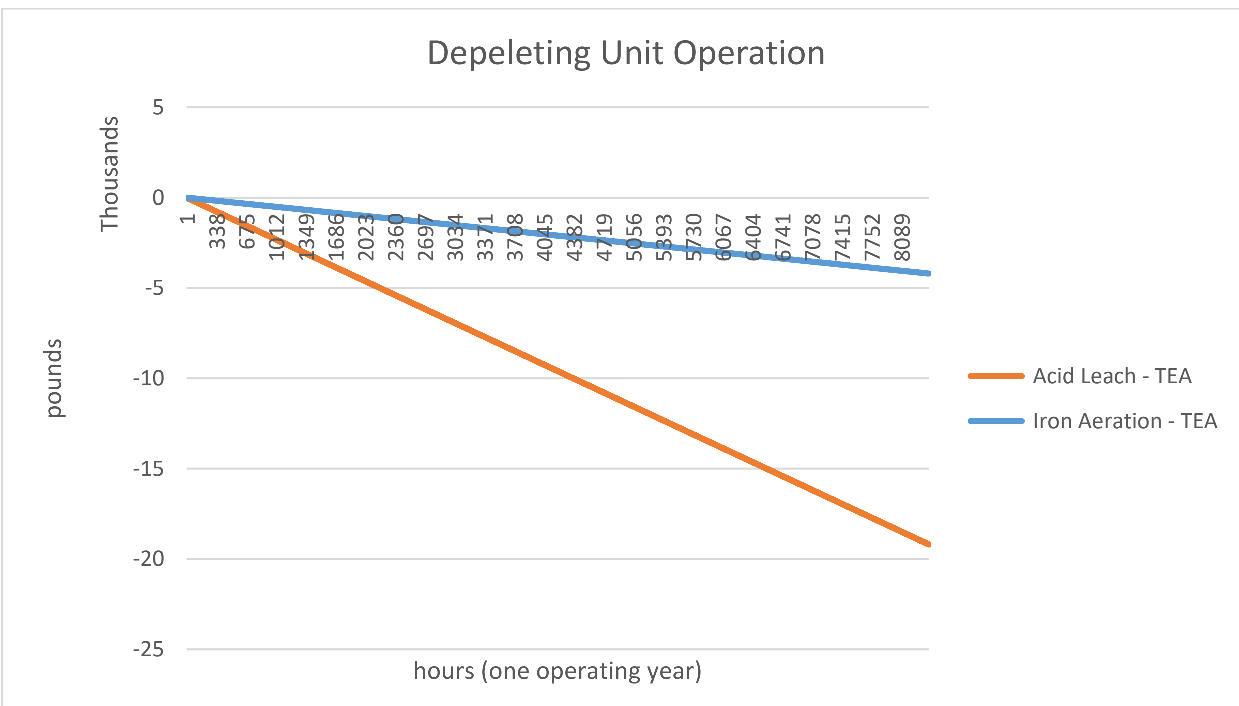

Figure 38 Process Unit Operations that are Depleting

6.2.3 Income Error Identification

While the flows in and out of unit operations may not agree and would have to be addressed to ensure a successful commercial implementation of this process, a comparison between the TEA and the simple dynamic model of the process on an economic front should be consistent. This is because the simple dynamic model uses the same flow rates as reported in the TEA. As shown in Table 18, for many of the costs and revenues there is only a very minor difference between the two but for several there is a significant difference. This is most apparent in the REE processing cost and the REE and metal income.

Table 18 Early REE TEA Model Comparison

		Barr TEA	**Simple SD**
Item	Detail	$/year	$/year
OPEX	Coal Cost	$ 525,000	$ 547,178
	Electricity, NG, Maintenance	$ 2,300,000	$ 2,299,920
	Steam	$ 47,914	$ 47,914
	Water	$ 51,626	$ 33,439
	Operator Labor	$ 400,000	$ 399,924
	Acid Cost	$ 493,806	$ 410,140
	REE + Ge and Ga Processing	**$ 244,608**	**$ 7,482**
	Base Metal Processing	$ 23,842	$ 14,508
	15% Misc. increase	$ 613,019	$ 564,076
	Total	$ 4,699,815	$ 4,324,581
Revenue	Activate Carbon	$ 10,430,000	$ 10,401,720
	Syngas	$ 799,092	$ 799,092
	REE and Metal	**$ 3,291,228**	**$ 2,039,982**
	Total	$ 14,520,320	$ 13,240,794
Net Revenue	Revenue - OPEX	$ 9,820,505	$ 8,916,213

A closer look at the REE mass flows shows the difference. As noted in the TEA report, the analysis of the coal and the process model uses REE in their elemental form but sales prices for REE are based on rare earth oxides (REO). To convert elemental REE mass to REO the following conversion is required which accounts for the additional oxygens and in some cases, multiples of the rare earth element. The typical oxide formula for each REO is shown in the following table and it appears the error is in the conversion of the mass flow of REE to REO in cases where there are two REEs in the REO. The following shows the conversion of a mass flow of REE to a mass flow of REO for a generic REO and a tabulated comparison of each element in Table 19.

$$Assume\ formual\ is\ RE_X O_y$$

$$REO\left[\frac{lb}{yr}\right] = REE_{recovered}\left[\frac{lb}{yr}\right] \times \frac{1\ lbmol\ REE}{molar\ mass\ REE}\left[\frac{lbmol}{lb}\right] \times \frac{1\ RE_X O_y}{X\ REE}\left[\frac{lbmol\ REO}{lbmol\ REE}\right] \times \frac{molar\ mass\ REO}{1\ lbmol\ REO}$$

Table 19 Rare Earth and Metal Flow Comparison

Element	**Concentration**	**Recovery**	**Salable Composition**	**TEA**	**Model**
	mg/kg	%		lb/yr Recovered	lb/year Recovered
Ce	154.8	80%	CeO2	4,820	4,820
Co	844	80%	Co	21,404	21,394
Cu	46	80%	Cu	1,166	1,166
Dy	13.2	80%	Dy2O3	771	384
Er	5.6	80%	Er2O3	325	162
Eu	5.8	80%	Eu2O3	338	170
Gd	19.7	80%	Gd2O3	1,150	576
Ga	17.5	80%	Ga2O3	1,193	596
Ge	18.9	80%	GeO2	690	796
Ho	2.2	80%	Ho2O3	129	64
La	53.7	80%	La2O3	3,195	1,596
Lu	0.6	80%	Lu2O3	37	17

Mn	28	80%	Mn	710	710
Nd	107	80%	Nd2O3	6,338	3,164
Pr	23.4	80%	Pr6O11	1,388	717
Sm	25.7	80%	Sm2O3	1,512	755
Tb	2.6	80%	Tb2O3	315	76
Tm	0.7	80%	Tm2O3	43	20
Sc	29.2	75%	Sc2O3	2,127	1,064
Yb	4.7	80%	Yb2O3	270	136
Y	39.4	80%	Y2O3	2,539	1,268
Zn	22.2	80%	Zn	563	563

The change in the REE and REO flow rates accounts for the largest difference in the economic comparison via the REE processing cost and the revenue from saleable REO.

The mechanism of discovery of this error is not a simply more diligent calculation but as observed in the review of spreadsheet error literature and the best practices of dynamic modeling build due in part to the nature of the equation formulation. In the TEA report it is stated that “This approach allows us to use published market prices for the REE/element oxide products to calculate gross revenue for the project…” (Mann, 2021) which implies the need for the rare earth elements and metals to be converted to their oxide from to be the products. The model formulation is used to support the conversion of the elemental concentration in the coal to the salable rare earth and metal oxide.

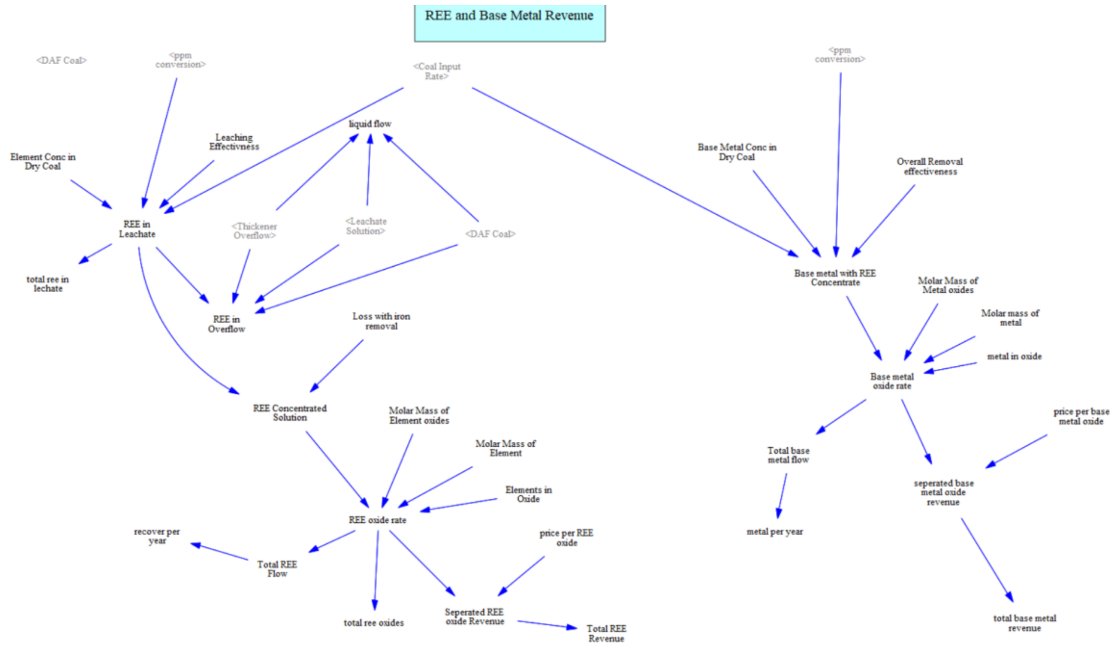

Figure 39 Rare earth and Metal Conversion and Revenue

The subscripting capability of system dynamics software allows for one structure to calculate all of the rare earth element and metal oxide product flows. In this structure, the flow rate of coal with the concertation of REE or metals determines the flow rate of the rare earth concentrate and the flow of metals in that concentrate. Then that element flow of material is converted to an oxide flow rate based on the chemical composition of the oxides. The product revenue is then the combination of the oxide flow rate and the price of the oxides.

6.3 Summary

TEAs are complex spreadsheets that can be compared to financial spreadsheets in for general estimates of the likelihood of errors. Approaching TEAs with dynamic modeling techniques allows for the analysis of the equations and assumptions in a manner that may root out errors that have been incorporated inadvertently. Such errors may impact both the technical aspects and economic aspects of a TEA.

CHAPTER 7

7 DYNAMIC TECHNO-ECONOMIC ASSESSMENT OF RARE EARTH ELEMENT EXTRACTION PROCESS

The elements developed for the generic TEA, the additional components from system dynamics literature, and the error mitigation properties of the dynamic TEA are used to evaluate a detailed TEA for the commercial scale process for rare earth element extraction from lignite coal. A comparison of both TEAs results with the same scope of what is considered in the model validates the dynamic approach. The application of the additional dynamic modeling elements to the TEA allows for a more robust estimate of the commercial process's economic performance and sets up the structure necessary to explore the model in a way that can lead to operational decisions regarding investment needs and timing of the various stages of development.

7.1 Application of Dynamic TEA Template to the REE Extraction Process

To effectively compare the standard approach with the dynamic approach to the TEA process an initial effort is made at replicating the spreadsheet-based TEA results using the dynamic TEA approach. This involved building on each of the generic TEA structures developed and applying them to the specifics of the commercial process.

7.1.1 Process Model

The process model for the rare earth extraction from lignite coal is a detailed model composed of roughly 30 process streams. It includes a stream table as well as a process flow diagram. While a detailed model of this process and the feedback relationships would be possible to build, due to the advanced nature of the process development and process parameter estimation, it was decided to assume the process model is optimized and maintain those desired ratios throughout any future optimizations. With that, the process model in this dynamic TEA is fairly straightforward and attempts to capture the key mass flows of the process and their relationship to a single feed, in this case, the coal.

The coal inflow is used as it is the main process parameter that all other process flows are based on as it is the key feedstock. Given this, the remaining reactants and outputs are calculated from the coal mass flow based on ratios derived from the stream table. Similarly, the product flows, in this case, a low ash coal product and recovered metals are derived from the incoming coal flow are based on the assumed recovery determined from the previous research (Mann, 2021). This also includes the assumed concentration of metals in the coal which is also derived from previous work (Laudal, 2017; Mann, 2021). With these values, the needed information is available for equipment scaling, capital cost estimation, operating cost estimation, the determination of the economic benefit of the process.

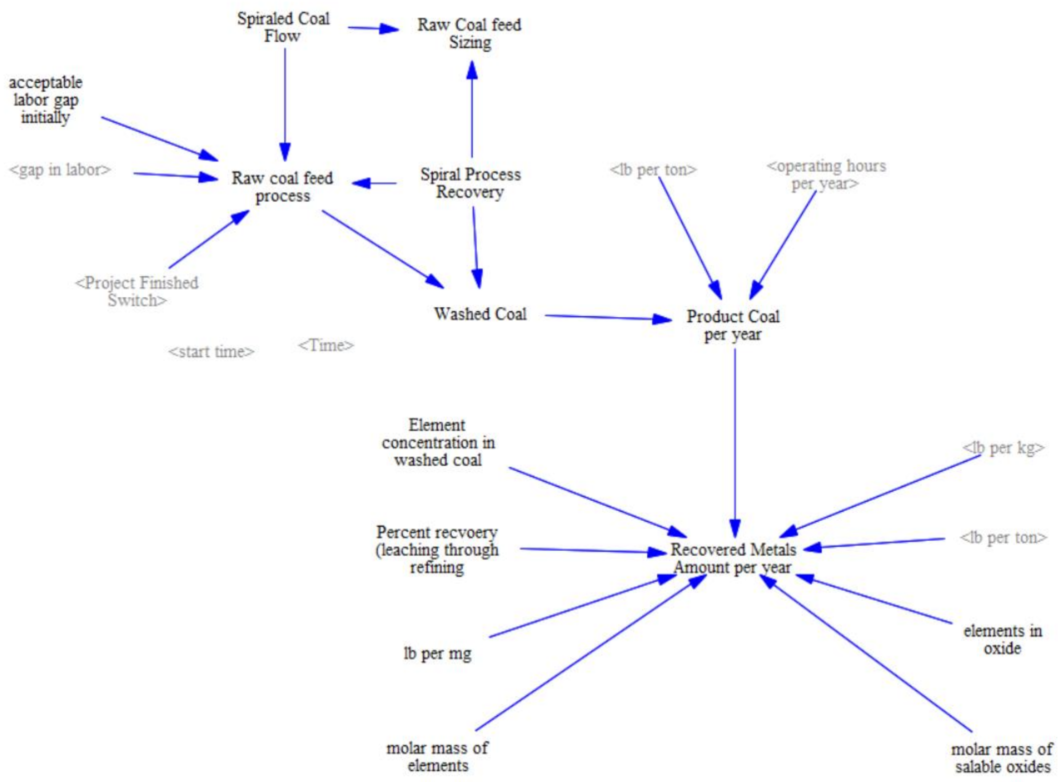

Figure 40 Rare Earth Process Model

7.1.2 Equipment Sizing

A scaling approach is built to account for adjustments to coal flow which is used as the key parameter for an adjustment of all equipment costs based on a plant scaling exponent as well as for water treatment costs as those were estimated separately from the process equipment in the initial TEA. This approach is used because of the detailed nature of the equipment estimate already conducted in the TEA. Over one hundred pieces of equipment are estimated for this process and then combined in the dynamic model as an overall mechanical equipment cost. This uses both tools, spreadsheet software, and modeling software, in ways that are best for each.

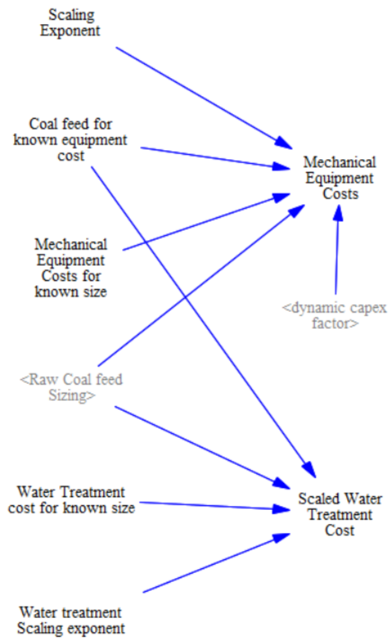

Figure 41 Rare Earth Equipment Scaling

7.1.3 Capital Costs

As stated, the mechanical equipment cost is outlined in detail in the spreadsheet TEA. Using this as a basis the remaining capital costs can be estimated with parameters as explored in the template dynamic TEA.

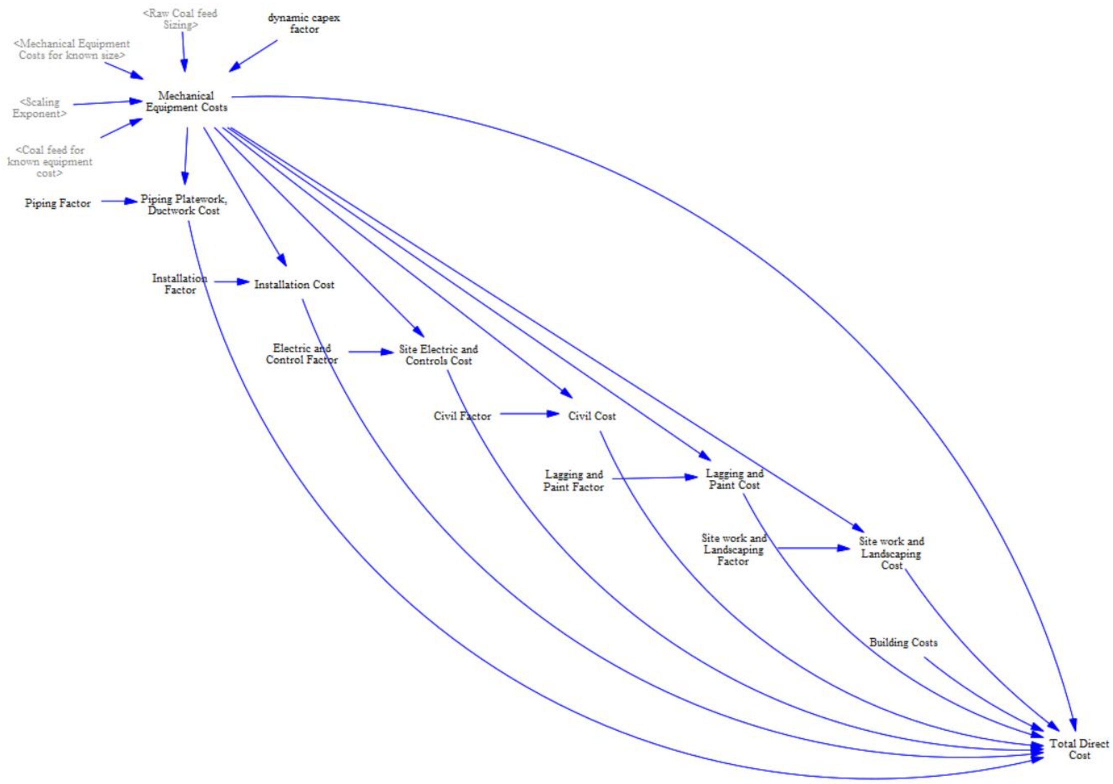

Figure 42 REE Process Direct Capital Cost

This approach captures much of the remaining costs for the plant including both the direct and indirect costs. Additionally, the capital cost of the wastewater process is broken out separately as that is a distinct process and designed separately. This also allows for comparisons to earlier models where the wastewater process was not included.

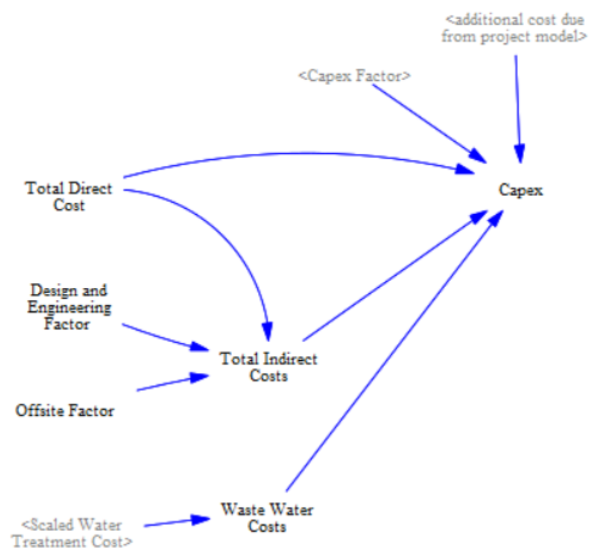

Figure 43 REE Process Total Capital Cost

7.1.4 Operating Costs

The process model approach defines the approach taken for estimating operating expenses. In this case, the various reactant and product flows are related to the standard coal rate and the specified rate in the model providing a ratio based on the coal flow rate.

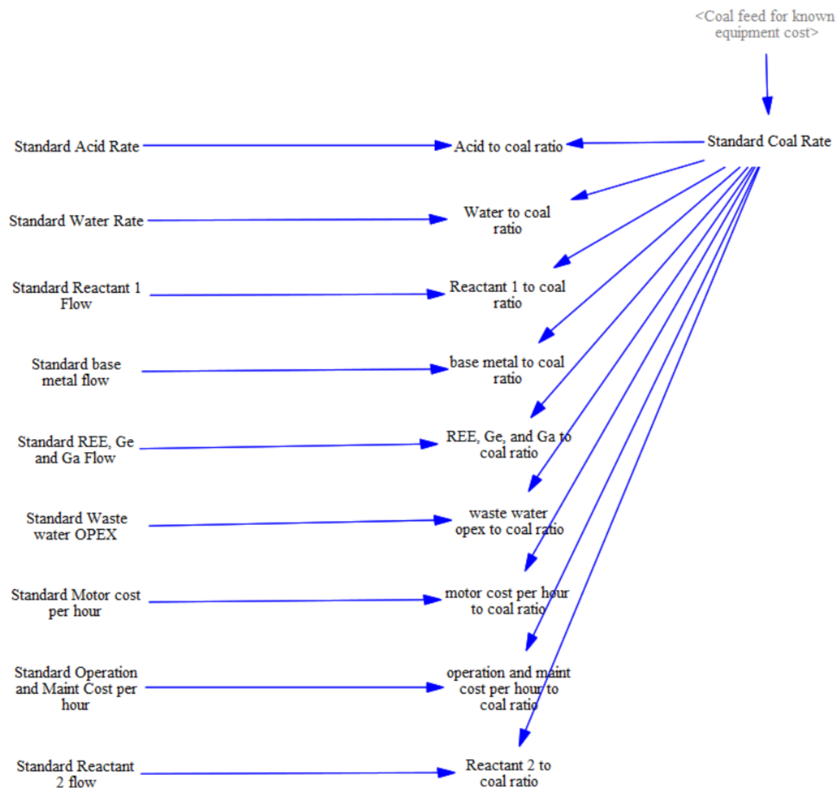

Figure 44 Operation Cost Ratios

These ratios are then used to calculate the flow rate of the reaming process elements which along with the cost of those components set the operating cost of the process. These include reactants, specialty processing costs, labor, and maintenance costs which sets the total operational cost of the process elements. This process cost is then used to determine the total operating cost which includes taxes, additional wastewater costs, and miscellaneous costs. Some of these costs are quoted material costs per mass or volume while others are estimates of costs for processing various components of the product material.

7.1.5 Income

The income for this process is based on two sources, one is the upgraded coal and the second is the metals extracted from the coal. The product prices are estimated based on industry research or discussions with experts in the field and used to set the revenue of the process. For this process, the coal revenue is the larger contributor to the overall revenue when compared to the recovered metal revenue, although the prescribed intent of the process is for metal recovery. As in the earlier TEA, the sale price is assumed to be separated REO rather than a mixed concentrate.

7.1.6 Economic Metrics

The economic metrics used for this analysis are several common ones, NPV, IRR, ROI, and payback period. These metrics account for the capital costs, operating costs, incomes, and in some cases expected interest rate and time frame to develop comparable metrics for evaluating this process's economic performance.

7.1.17 Sensitivity Testing

The ranges used for sensitivity testing are similar to the assumptions in the initial TEA (Mann, 2021):

- Worst Case
  - The total CAPEX of the Base Case is increased by 25%
  - The total OPEX of the Base Case is increased by 25%
  - The income from the upgraded coal of the Base case is decreased by 10%

  - The income from the recovered metals and REE of the base case is decreased by 10%
- Best Case
  - The total CAPEX of the Base Case is decreased by 25%
  - The total OPEX of the Base Case is decreased by 25%
  - The income from the upgraded coal of the Base case is increased by 10%
  - The income from the recovered metals and REE of the base case is increased by 10%

This sensitivity analysis is conducted by adding factors to the CAPEX, OPEX, and revenues that can be changed to match the specified range. Then the three cases are simulated individually, and their results are reported.

7.1.8 User interface

There is a substantial user interface and operational guide included in this spreadsheet TEA. Guidance as to cell coloring, macro usage, and revisions to the model is provided in a “readme” tab. Along with the guide are three detailed dashboards for overall economic analysis, CAPEX and OPEX for the main process, and CAPEX and OPEX for the wastewater treatment process. Many plots and tables are provided to show the result of various choices regarding coal product pricing, various process recovery percentages, and which REE and metals should be included in the analysis. The values of these plots and tables change with changes to the input assumptions by the user.

These dashboards provided a good template to develop the dashboard within the dynamic model. While not all of the same charting capability exists across all software the critical information to be communicated and needed inputs from the user can be replicated in both spreadsheet software and dynamic modeling software.

7.2 Core TEA Comparison

To validate the core elements of the dynamic TEA, comparisons can be made to the economic metrics from the spreadsheet TEA using the same key inputs and parameters. As described above, the flow rates, ratios, factors, and costs can be entered just as they exist in the spreadsheet TEA. Without any added dynamic elements this should result in the same outputs. This should be true for all three cases described in the sensitivity analysis. The values provided are normalized to the base case in this comparison to conceal the specific economic results of the TEA.

Table 20 Comparison of Core Model and Spreadsheet TEA

	Dynamic Base/ TEA Base	**Dynamic Best /TEA Best**	**Dynamic Worst /TEA Worst**
Economic Metric	**Base**	**Best Case**	**Worst Case**
CAPEX	1.00	1.00	1.00
OPEX	1.00	1.00	1.00
REE and Base Metal Payable Amount per year	1.04	1.04	1.04
Upgraded Lignite Coal Payable Amount per year	0.99	0.99	0.99
Profit (after income tax*)	1.02	1.01	**0.75**
Simple Payback (years)	0.98	0.99	**1.34**
IRR (10 years)	1.03	1.01	
ROI (10 years)	1.03	1.01	**0.78**

NPV (10 years) @12% discount rate	1.06	1.01	**0.24**

Several of the Worst-Case economic metrics are observed to be significantly different than the spreadsheet TEA. As the results for the Base Case and Best Case are reasonably close for those parameters an investigation was made into the differences between the spreadsheet TEA and the dynamic TEA. Due to the complex nature of the spreadsheet model and the previously cited research on the potential for errors in the spreadsheet model, the found errors are not unexpected.

First is the application of taxes on the profit. In the dynamic TEA, the formulation for profit after taxes utilized a conditional statement to verify that the profit value was positive before applying the tax. While a business may need to pay some taxes even when income is negative such as income and excise taxes these are not the same as income tax and would not be levied based on the profit (Otis, 2017). In the dynamic TEA taxes were not applied to the negative income of the Worst Case, however, in the spreadsheet TEA the tax was applied to the negative income thus adding a large additional cost to the already negative income. By alerting the dynamic TEA to account for tax in this manner, although not correct, the results can be compared.

Table 21 Comparison of Core Model and Spreadsheet TEA with Tax Correction

	Dynamic Base/TEA Base	Dynamic Best/TEA Best	Dynamic Worst/TEA Worst
ECONOMIC ANALYSIS	Base	Best Case	Worst Case
CAPEX	1.00	1.00	1.00
OPEX	1.00	1.00	1.00
REE and Base Metal Payable Amount per year	1.04	1.04	1.04
Upgraded Lignite Coal Payable Amount per year	0.99	0.99	0.99
Profit (after income tax*)	1.02	1.01	1.00
Simple Payback (years)	0.98	0.99	1.00
IRR (10 years)	1.03	1.01	
ROI (10 years)	1.03	1.01	1.00
NPV (10 years) @12% discount rate	1.06	1.01	**0.29**

The adjusted calculation to the tax creates a greater alignment between the profit, payback period, IRR, and ROI but the NPV calculation is still significantly different. Additional investigation yields another spreadsheet error of a negative 12% interest rate used in the Worst Case. Applying this adjustment to the TEA results in good agreement between all economic metrics.

Table 22 Table 21 Comparison of Core Model and Spreadsheet TEA with Interest Rate Correction

	Dynamic Base/TEA Base	Dynamic Best/TEA Best	Dynamic Worst/TEA Worst
ECONOMIC ANALYSIS	Base	Best Case	Worst Case
CAPEX	1.00	1.00	1.00
OPEX	1.00	1.00	1.00
REE and Base Metal Payable Amount per year	1.04	1.04	1.04

Upgraded Lignite Coal Payable Amount per year	0.99	0.99	0.99
Profit (after income tax*)	1.02	1.01	1.00
Simple Payback (years)	0.98	0.99	1.00
IRR (10 years)	1.03	1.01	0.00
ROI (10 years)	1.03	1.01	1.00
NPV (10 years) @12% discount rate	1.06	1.01	1.00

With the agreement between the dynamic TEA and the spreadsheet TEA, albeit accounting for errors that exist in the spreadsheet version, the remainder of the model calculations have been validated. The minor differences in the results are due to the rounding of values used in the spreadsheet TEA that is not applied in the dynamic TEA.

While the Base Case and Best Case generally agreed in the initial comparison, the Worst-Case difference results in a much more positive outcome of the economic performance of the project. The following table, also normalized, shows the scale of the changes with the dynamic TEA. A negative ratio means that the Worst-Case value was negative and the Base case was positive.

Table 23 Scale of Change on Worst Case from Core Dynamic TEA

ECONOMIC ANALYSIS	Spreadsheet Worst Case/Spreadsheet Base Case	Dynamic TEA Worst Case/Spreadsheet Base Case
CAPEX	1.25	-1.25
OPEX	1.25	-1.25
REE and Base Metal Payable Amount per year	0.90	0.94
Upgraded Lignite Coal Payable Amount per year	0.90	0.89
Profit (after income tax*)	-3.60	-2.68

Simple Payback (years)	-0.35	-0.47
IRR (10 years)		
ROI (10 years)	-5.44	-4.22
NPV (10 years) @12% discount rate	-49.31	-12.00

The largest change is seen in the NPV where the Worst Case NPV decreased from a negative 49 times the Base Case NPV to negative 12 times the Base Case NPV. While this is still a negative NPV it is substantially better by a factor of 4.

7.3 Dynamic TEA Comparison

With the confirmation of the core elements of the dynamic TEA, the additional dynamic components previously discussed can be added and the resulting changes to the economic parameters can be evaluated. The included components are a model of the construction portion of the project, a rare earth market pricing model, and a hiring model.

7.3.1 Integrated Project Model

The project model is applied similarly as was explored in Chapter 4. Using the planned factors of the portions of the capital cost that would have some form of installation labor associated allows for an estimate of the labor needed to complete the construction of the process that is included in the capital cost.

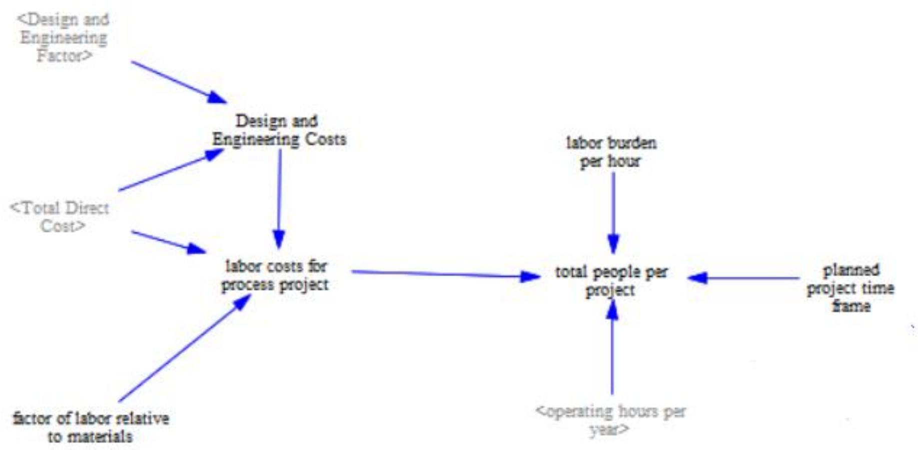

Figure 45 CAPEX Factors to Project Model Inputs

This estimate is based on the factor of labor for the direct costs as well as the added design and engineering cost as that is assumed to be labor, not equipment cost. That gives the total cost of labor for the project as planned from the capital cost estimation. The planned project duration, the operating hours per year, and the cost per hour of labor (labor burden) allow for a calculation of the total people working on the project for the process construction and implementation phase which fits with the capital costs.

The remainder of the project model is used to calculate the total cumulative labor hours for the project with the various project dynamics effects included. In this case, the effects of precedence of tasks, errors that are created on errors, implications of staff increase, and the rework cycle drive the total hours over the planned hours as well as moving out the completion date. The project as proposed was to be built in 1 year but with the inclusion of the project model, the estimated completion is almost 1.4 years at an additional labor cost of 1.63 times the planned labor cost. These impacts are then added to the overall capital cost and change the time when revenue can be earned.

7.3.2 Integrated Pricing Model

The proposed commodity pricing model is used as discussed in Chapter 4 with the price projections out through the end of the project timeframe. The integration of the price estimates with the method that the dynamic TEA model calculates the rare earth and metal income requires a conversion of the output of the pricing model with the revenue. The cost of mixed oxides per ton is used as the price for the pricing model and to initialize the price an equilibrium price is assumed as stated previously. The ratio of the mixed oxide price to the equilibrium price is used to increase or decrease the revenue as a multiplicative factor on the revenue. A more detailed pricing model would consider the rare earth elements and metals as separate, but in this case, the bulk mixed oxide price allows for a better estimate of future prices than a single historical price applied across the entire project. For the Base Case, the rare earth and metal revenue shows some dynamic behavior as compared to the spreadsheet TEA pricing with the specific numbers removed.

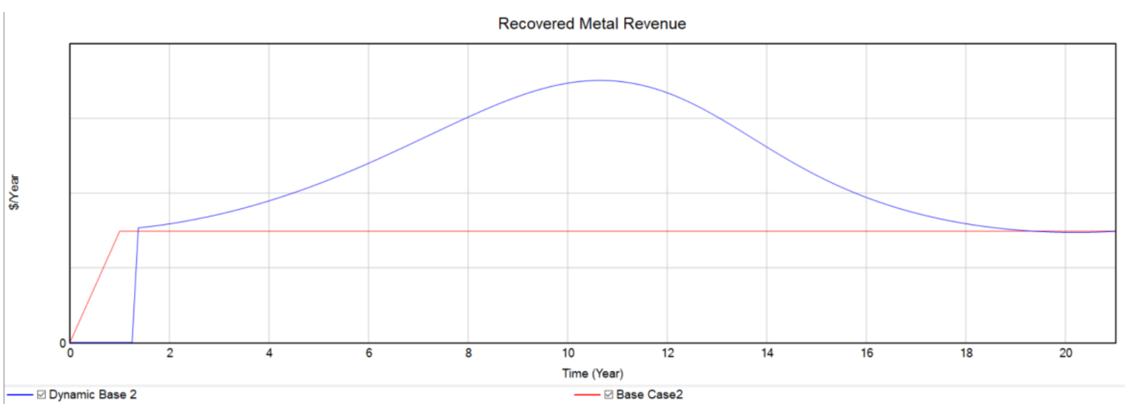

Figure 46 Comparison of Metal Revenue with Dynamic TEA and Spreadsheet TEA

7.3.3 Integrated Hiring Model

With some estimated parameters for the time to transition between stocks, the dynamics can be observed which requires high recruiting initially to get candidates which drops off as the staff level nears the target but not completely as there is always attrition in either the new hires or the experienced personnel which have to be replaced.

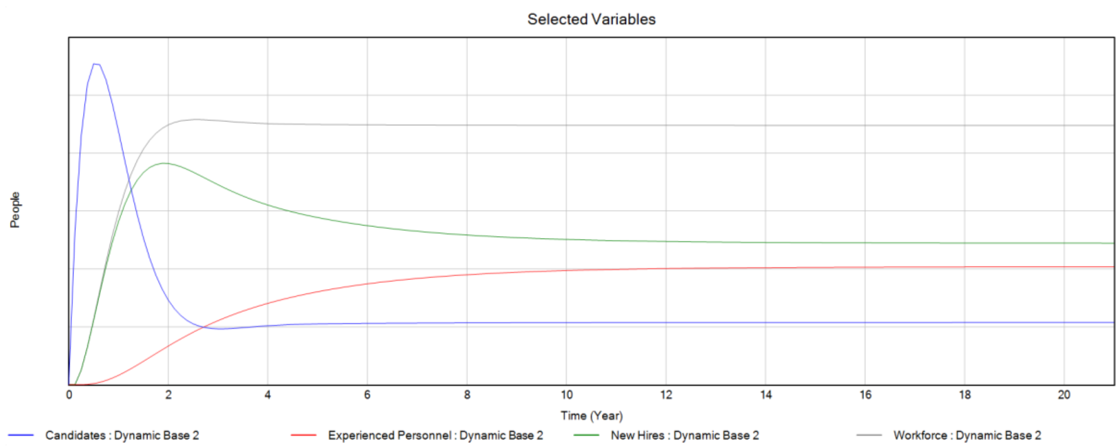

Figure 47 Needed People in Each Stage of Hiring Process to Support Project

This type of information is relevant for early policy decisions on hiring and spending toward staff accumulation. In this case, the staff is approaching the needed level by mid-year one which is about when the plant construction phase is coming to an end.

7.3.4 Case Comparison

With the integration of the above dynamic modeling elements, a comparison can be made to the spreadsheet TEA economic metrics Best Case and Worst Case, but some care must be taken as to how the best and worst case parameters are set. In the spreadsheet TEA there is an increase and decrease in the CAPEX, OPEX, product coal revenue, and REE and metal revenue. Several of those parameters cannot be directly altered in the dynamic model without ignoring the intended dynamics. With that in mind, Table 24 shows how an attempt was made to replicate the intent behind the spreadsheet-based sensitivity parameters within the dynamic TEA.

Table 24 Replication of Sensitivity Parameters in Dynamic TEA

	Best Case	Dynamic Best Case	Worst Case	Dynamic Worst Case
CAPEX	-25%	-25% equipment cost 5% normal error fraction	+25%	+25% equipment cost 25% normal error fraction
OPEX	-25%	-25%	+25%	+25%
Product Coal Revenue	+10%	+10%	-10%	-10%
Rare Earth and Metal Revenue	+10%	+10% factor on demand growth fraction	-10%	-10% factor on demand growth fraction

While these parameters do not exactly matched with the spreadsheet TEA cases it allows for an initial evaluation before a more robust sensitivity analysis on a broader set of parameters.

Table 25 Results of Simple Sensitivity Application to the Dynamic TEA

	Dynamic Best Case/ Spreadsheet Best Case	Dynamic Worst Case/ Corrected Spreadsheet Worst Case	Dynamic Worst Case/ Corrected Spreadsheet Worst Case
CAPEX	1.1	1.6	1.6
OPEX	1.0	1.0	1.0
REE and Base Metal Payable Amount per year	2.4	2.5	2.4
Upgraded Lignite Coal Payable Amount per year	1.0	1.0	1.0
Net Annual Revenue (after income tax)	1.8	0.2	0.2
Simple Payback (years)	0.6		
IRR (10 years)	1.4		
ROI (10 years)	1.2	0.2	0.3
NPV (10 years) @12% discount rate	1.2	0.1	0.4

While the CAPEX is higher for the dynamic cases as indicated by the ratio larger than 1, many of the economic metrics are also better for both the best case and the worst case. This includes the net revenue after tax which is higher in the best case and less negative in the worst case as well as the NPV which is also higher in the best case and less negative in the worst case. Even with the correction for the found errors there is a benefit in the dynamic TEA over the corrected worst case spreadsheet TEA.

7.3.5 Sensitivity Analysis

As was shown to be common in the TEA literature and the analyzed REE TEAs, a sensitivity analysis can identify the range of outcomes that are likely given a provided range of input parameters. The range of parameters can be at an aggregate level, as was done above, or at a single variable level easily in dynamic modeling software such as Vensim. In the case of the dynamic TEA, the entire set of parameters has been used in the sensitivity analysis, along with the range of the analysis. In all cases, a random uniform distribution was used in which any value is just as likely as any other to occur (Weisstein, n.d.).

For the initial sensitivity analysis, the same ranges relative to the standard TEA were used but on a broader set of parameters. The capital costs and operating costs elements have a range of -25% to 25% of the base case while the revenue elements have a range of -10% to 10%. With this starting point, the sensitivity over 200 simulations can be simulated, and results for the various parameters obtained.

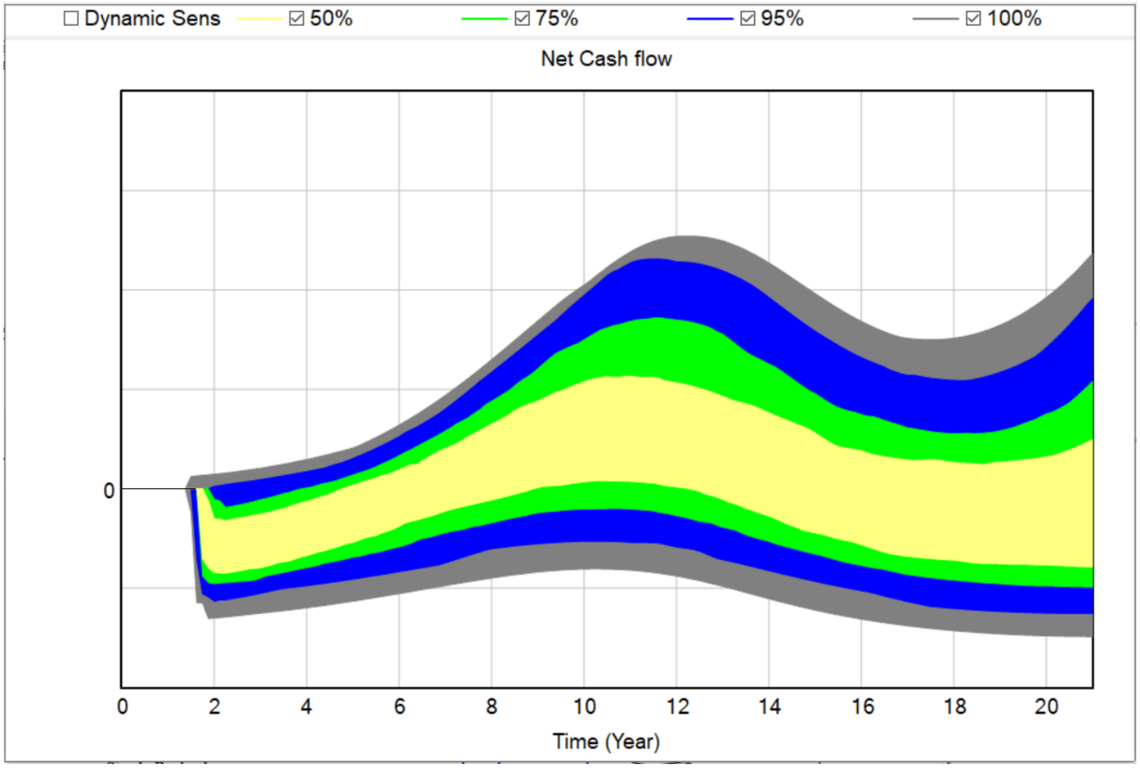

Figure 48 Sensitivity Analysis on Net Cash Flow - All Parameters

One area the dynamic model sensitivity analysis can be used with more intention is the rare earth market growth. The nominal case assumes the growth of demand to be aligned with GDP growth, but this does not consider the potential growth in the market for rare earth elements. Financial predictions of the rare earth market expect much higher growth than expected from just GDP, one such estimate indicates a doubling of the market is likely from 2021 to 2028 (*Rare Earth Market*, 2021). Using a range on the growth rates of ½ of the expected GDP growth up to two times the GDP growth in the sensitivity analysis while keeping the rest of the ranges the same shows a different potential economic outlook. The growth of demand aligns with the expectation of doubling in seven years.

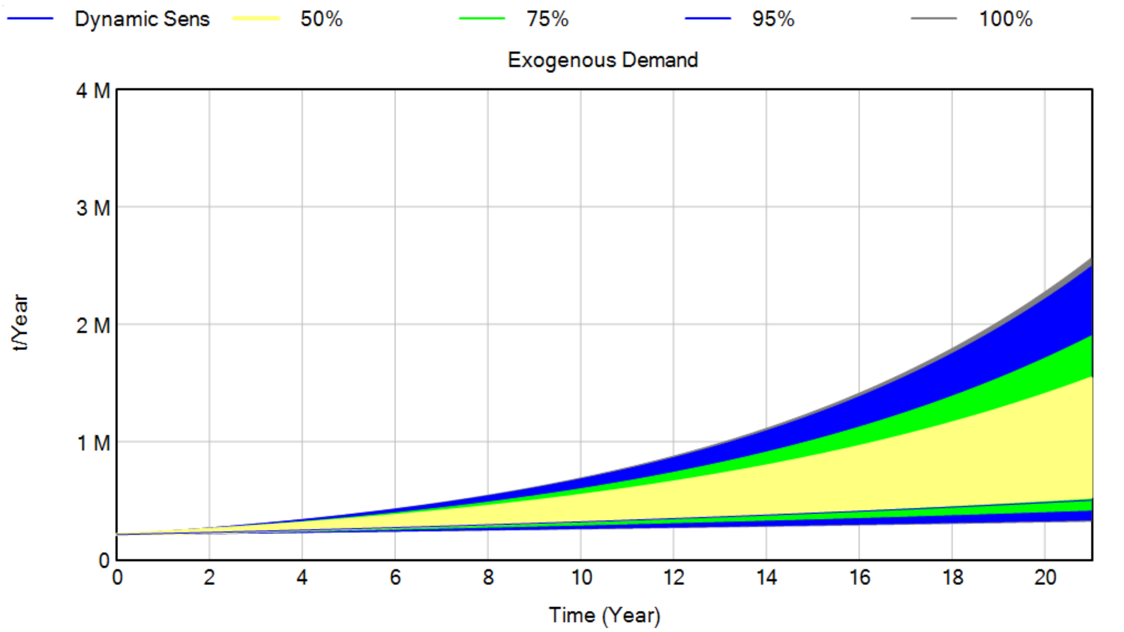

Figure 49 Rare Earth market demand using more likely growth range

With this range of demand growth, the economic outcome of the process changes such that the economic upside increases substantially. Along with a minimal increase in the economic downside.

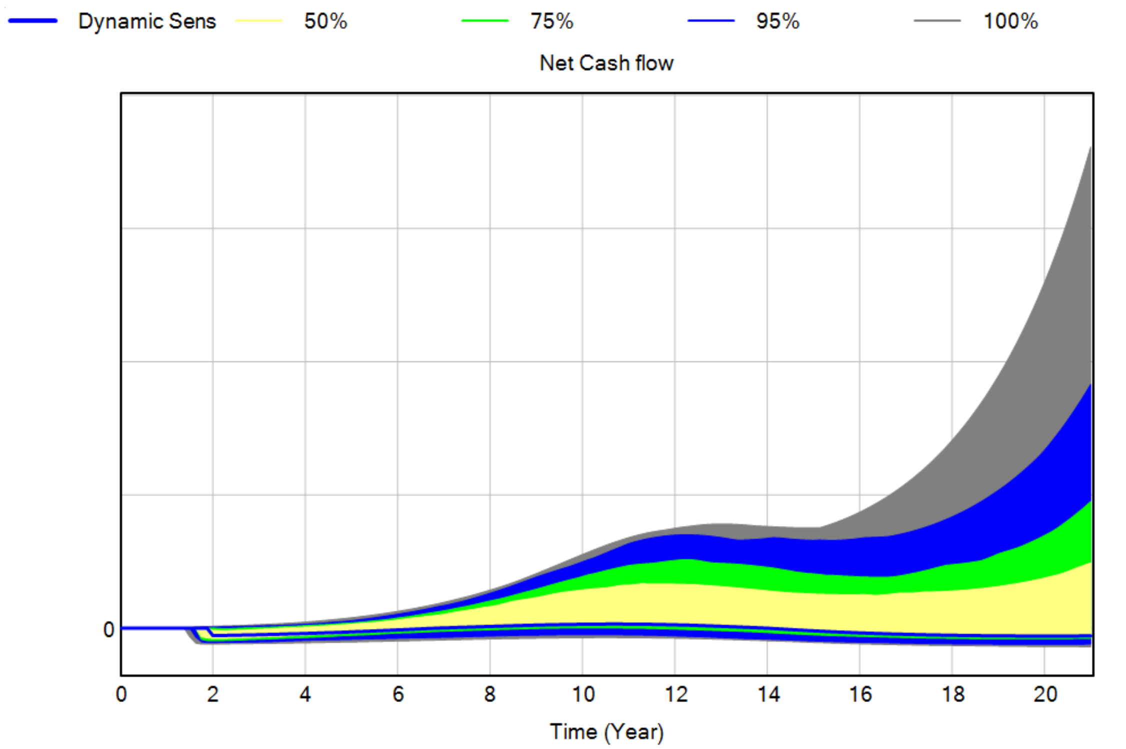

Figure 50 Net Cash flow using more targeted sensitivity parameters

7.3.6 Management Flight Simulator

An additional use of the dynamic TEA is in the form of a management flight simulator (MFS). This can be used to help guide decisions and allow model users to explore variables in a more experiential format rather than just the outputs of the simulation. Setting up an MFS requires the specification of variables that can be specified by users in the real world. These variables then can be modified by model users and the results of their choice seen until the next time step where a decision is needed. As one of the goals of performing the TEA is an evaluation of the economic performance of the project, an MFS allowing for users to explore the range of investment parameters chosen in a format that allows for an additional degree of learning. The types of variables that may be relevant to the experience of an MFS would be the amount and timing of investment levels, hiring choices and timing, and project planning parameters. Users of the MFS may gain an understanding of how the timing and magnitude of their decisions change the outcome of the commercialization effort.

7.3 Summary

The application of the generic TEA framework to an advanced REE extraction spreadsheet-based TEA allows for the replication of the results when factored for discovered errors. This matched core TEA can then be built upon with the additional modeling components identified in the system dynamics business research and applied to TEAs in Chapter 4 to provide additional analysis of the possible ranges of economic performance. These additions also set up the dynamic TEA for transition to an operational model which can be used by stakeholders for understanding the likely outcomes of the model and what impacts managerial decisions may have on those outcomes.

CHAPTER 8

8 COMPARISON OF TEA DEVELOPMENT OVER TIME

As the REE project has been developing over several years there are several versions of the TEA that have been created and captured through the process. Only one can be published but comparisons between them provide insight into the development of TEAs over time. This is not at the level of revision to revision but more generational.

8.1 TEA Comparison Over Time

The first TEA was published by Laudal in 2017. The focus of this 2017 TEA was the production of activated carbon as well as the mixed rare earth concentration. This included the integration of the REE process with another process to utilize confidential data, but utilized additional test data and was created in 2019. This 2019 TEA increased the process mass flow which had beneficial effects on the capital costs due to scaling effects. Along with the increase in the process flow, the additional process development between the 2017 TEA and the 2019 TEA caused a substantial increase in operating expenses due to additional process steps which have feed materials needed. The offset between increased revenue due to the additional product produced is offset by the larger operating cost. Finally, a 2021 TEA substantially increased the size of the process which resulted in a large decrease in the capital cost per ton processed due to the sustainable scale increase. There is also some optimization of the operating costs such that on a per ton processed basis.

8.2 Summary

One result from the comparison of these TEAs as they developed is the drive for increased process size due to the benefits of scale on equipment cost. Also, the main changes through the TEAs involved the operating expenses, which shows the benefits of the staged development where actual operating conditions are identified and developed to best estimate those costs.

CHAPTER 9

9 DISCUSSION OF THE DYNAMIC TEA APPROACH

A discussion of the research as it pertains to the research hypothesis and questions allows for the evaluation of the strengths and limitations of this work. Future directions based on this work's strengths and limitations are then explored and finally, the relevance and conclusions based on the research conducted are provided.

9.1 Discussion

9.1.1 Research Question 1

Within the TEA literature that uses system dynamics, there are various examples of elements of the TEA built using dynamic models. There are no examples of a holistic dynamic modeling approach that offers additional benefits as compared to modeling different aspects of the process with different tools. This work considers how to build a TEA that matches a typical TEA's results but as a complete dynamic model using the same building blocks as are common in a TEA. These generic elements can be combined into more complex TEAs as shown by applying the generic dynamic TEA framework to the rare earth element extraction process. The framework developed in Chapter 4 was applied in Chapter 6 and Chapter 7 to two versions of the rare earth extraction spreadsheet TEAs. Both versions had differences that required modifications, but the starting point of the generic dynamic TEA allowed for the implantation of both models on a common backbone that included the key elements within a standard TEA approach.

9.1.2 Research Question 2

Based on a review of the TEA literature in Chapter 2 as it pertains to rare earth elements and the use of system dynamics modeling in TEA, it is clear that common components have been created with a system dynamics approach (Elizondo-Noriega et al., 2021; Proaño et al., 2020). Even within those applying system dynamics to the TEA, there are only minor attempts to utilize past work in dynamic modeling to support elements of a TEA that are not commonly modeled. In the rare earth TEA specific literature there is not any reference to the project aspect of these processes, minimal consideration of product pricing changes over time, and the workforce needs of the process (Deng et al., 2021). The addition of these to the standard TEA components, all within a dynamic framework, allows for a more robust picture of the performance of the process by considering aspects that will likely exist and may change the amount or timing of the economic returns. As shown in Chapter 5, elements such as the project model can be applied to TEAs using information that is typically available to TEAs and can afford an alternative outcome to the construction and start-up phase of a project which is a critical time period for the economic performance. Dynamic pricing has been explored but not in such a way that elements that drive the price of the product are incorporated in the TEA which can allow for a more detailed analysis of the implications of external conditions on the economic performance of the project. In terms of the operation economics, investigations of the labor and staffing plan ensure that the staffing can be brought online in sufficient time to meet the commercial objectives of the project and with the model decisions on when and how many people should be hiring are available.

9.1.3 Research Question 3

The research on spreadsheet errors has not reached into the technical modeling space but the same mechanisms that cause errors in financial spreadsheets are likely to occur in technical spreadsheets (Panko, 2008a). This was confirmed by observing errors in the examined TEAs in both Chapter 6 and Chapter 7. The method of discovery of these errors was not that of diligent review, but by constructing the TEA as a system dynamics model, there are inherent advantages to error discovery and prevention that do not exist in the same way in spreadsheet tools. System dynamic models rely on unit checking which can prevent simple calculation mistakes as seen with the rare earth element to oxide conversion. Also tracking the behavior over time of variables allows for determining issues in mass balances as shown with the process model in system dynamic form. The visual connection of the equations also prevents logical issues as any calculation using that variable must show that variable as connected and causing it, this can prevent different calculations using different variables when it should be the same such as with the coal mass flow. Additionally, a form of reality is easily built into equations to prevent the use of parameters when it is not correct such as applying the tax to a negative profit. Finally, scenarios can be run on the same model where only the parameters in question are changed which prevents unintentional differences between scenarios such as seen with the erroneous negative discount rate. All of these aspects were caught, not by diligent checking but due to the inherent process involved in building a dynamic model.

9.1.4 Research Question 4

Using the sensitivity analysis capability of system dynamics to evaluate a broader range of parameters provides multiple benefits. In the case of the rare earth element extraction process, a more likely range of rare earth element pricing was used within the sensitivity analysis which shifted the potential net cash flow from straddling zero to a much larger percentage being positive as shown in Chapter 7. The range of prices is also supported by research into expected price increases based on market growth rather than being a nominal range of potential prices (*Rare Earth Market*, 2021). While the specifics of the changes cannot be shown due to confidentiality, there is an observable change in the trend of the economic outcomes relative to the sensitivity analysis as applied similarly to the spreadsheet TEA. This change in outcomes may make for a much more attractive process from an investment perspective while also including more realistic ranges of costs due to the robust sensitivity analysis. The optimization capability of system dynamics was not used as the feedback loops that would be necessary to constrain the optimization were not included and without such feedback effects the optimization simply increased the size of the plant due to the benefit of decreasing capacity costs per unit of flow with increased size.

9.2 Strengths and Limitations

The observed boundaries of a typical TEA and a review of the common business problems that are considered by dynamic modeling allowed for seeing what was missing in the typical TEA approach. This was confirmed by some literature emphasizing the need for additional elements to be added to a standard TEA approach.

The aspects that were not included were chosen based on previous research as well as by what was hypothesized to be significant to the outcome of the TEA but the additions are nowhere near exhaustive. There is a long history of system dynamic modeling for business, environmental, and social problems that could be pulled on to add elements other than what has been considered in this work. The benefit of what has been shown is how easily these previous works can guide additions to a dynamic TEA depending on the need of the TEA and the process.

By having a clear template in relativity generic terms, this work provides an easy starting point for future TEAs intending to use a dynamic modeling approach. The generic dynamic TEA includes the types of calculations observed in the review of rare earth TEA literature but may not include all common elements. Additionally, the calculation approach may not be relevant to every TEA due to the specifics of the equipment, process, or income approach. This is especially true for processes that do not make a product but instead reduce the cost of a process, which were not considered in this work as that was not a common outcome of the reviewed standard TEAs. One area that is more complex in dynamic modeling tools is a detailed process model due to the need to track material flows and energy flows in detail. This is possible but was not explored in detail in this work as the process parameters had been developed in detailed laboratory settings. This approach does require a familiarity with the modeling methodology and tools which are not commonly used as compared to the nearly ubiquitous use of spreadsheets, but the benefits of this approach may offset the initial learning challenges.

Errors were immediately discovered when replicating TEAs using the dynamic TEA approach. Correcting these errors caused large changes in the reported economic metrics, which as a target outcome of a TEA is a useful result. Dynamic modeling is not immune to the introduction of errors, but the process used in this work does help to prevent it. A limitation of this work is that the dynamic models were not checked for errors on their own and other issues may have been incorporated.

Using the sensitivity analysis features, a full range of parameters can be analyzed simultaneously which allows for a more robust sensitivity analysis. This does require a more detailed investigation of the parameters involved which can be more work, but the results can change the range of outcomes in the process.

9.3 Future Directions

This work has pushed several areas of the TEAs forward, but many future directions remain. Additional dynamic elements that would support the outcome of TEAs likely exist in prior work and can be applied to the dynamic TEA approach with modifications.

Developing more integrated process models is one area where system dynamics could be applied that would support stronger TEAs. By incorporating the unit checking capabilities, accumulation, and rates a more comprehensive process model could be incorporated and allow for additional sensitivity analysis, especially around areas like process efficiency which may drive additional research directions. There may also be aspects of the process model that provide a balancing effect to the economic push to increase the size of the process that can be added. This could also include more environmental aspects of the modeling process to cover more of the environmental criteria that future projects may be subject to.

In the spirit of process optimization, additional support for the research and development needs of the process may be incorporated which may allow TEAs that are much earlier in the process to have a better understanding of the costs to achieve the targets necessary for commercialization of the process.

The development of more useful user interfaces and MFS may also benefit the outcome of projects using this methodology. The dynamic model that can be run much like a digital twin of the project will allow for various stakeholders such as investors, governmental entities, and the general public.

9.4 Conclusions and Significance

This work intended to evaluate the application of system dynamics to TEA to evaluate if the benefits of system dynamics methodologies could enhance the outcome of a standard TEA. The methodology was applied to a novel rare earth extraction process developed at the University of North Dakota. A generic dynamic approach was developed based on the common elements identified from the literature on TEAs related to rare earth elements and building upon what work has been undertaken in applying system dynamics to portions of TEAs. Several versions of spreadsheet-based TEAs for this process have been compared with the dynamic approach. No clear ability to predict the changes over time of the spreadsheet TEAs for the REE project appeared with the dynamic TEA as developed. However, the dynamic TEA discovered errors in the spreadsheet TEA via the normal development process and equation formulation, and a more specific set of sensitivity analyses provided a more positive economic outlook for the commercial process.

As novel technologies are developed, their commercial applicability can be evaluated and supported in a more robust manner, encouraging their successful implementation. The generic approach outlined in this work can be applied to existing spreadsheet-based TEAs or novel processes in such a way that fewer errors and more robust results can be obtained from TEAs, leading to better investments and more successful project outcomes to meet the challenges facing the energy industry.

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APPENDIX A

Table 26 Sensitivity Parameters for Generic Dynamic TEA

	Initial	Min	Max
Admin Cost factor	0.1	0.09	0.11
Buildings	0.1	0.09	0.11
Construction Expenses	0.41	0.369	0.451
Contingency	0.44	0.396	0.484
Contractor's Fee	0.22	0.198	0.242
Conversion to product	0.5	0.45	0.55
Cost per operator	75	67.5	82.5
Depreciation Factor	0.05	0.045	0.055
Direct Supervisor and clerical labor factor	0.1	0.09	0.11
Distribution and Sales Factor	0.2	0.18	0.22
Electrical systems	0.11	0.099	0.121
Engineering and Supervision	0.33	0.297	0.363
Equipment Installation	0.47	0.423	0.517
Flow of Reactant 1 relative to key material	1	0.9	1.1
Flow of Reactant 2 relative to key material	2	1.8	2.2
Heat capacity of mixture	1	0.9	1.1
Instrumentation and Controls	0.36	0.324	0.396
interest rate	0.1	0.09	0.11
Key Material Cost per unit	0.1	0.09	0.11
Key Material Flow	1000	900	1100
Key Material SG	1	0.9	1.1
Lab charge factor	0.1	0.09	0.11
Legal Expenses	0.04	0.036	0.044
Local Taxes and Insurance Factor	0.035	0.0315	0.0385
Maintenance and repair factor	0.001	0.0009	0.0011
Operating Supplies factor	0.02	0.018	0.022
Operators needed	5	4.5	5.5
Patent and Royalty Factor	0.05	0.045	0.055
Piping	0.68	0.612	0.748
Plant overhead Factor	0.1	0.09	0.11
Product Price per unit	200	180	220
pump eff	0.6	0.54	0.66
Pump head	100	90	110
Pump Scaling Exponent	0.6	0.54	0.66
Reactant 1 cost per unit	0.1	0.09	0.11
Reactant 1 SG	2	1.8	2.2

Reactant 2 cost per unit	0.1	0.09	0.11
Reactant 2 SG	3	2.7	3.3
research and development factor	0.2	0.18	0.22
Residence Time Needed	1	0.5	1.5
Service Facilities	0.7	0.63	0.77
Temp increase Needed	100	90	110
Time from start to earn income	1	0.9	1.1
Waste Treatment cost per unit	0.1	0.09	0.11
working capital	0.15	0.135	0.165
Yard Improvements	0.1	0.09	0.11

APPENDIX B

Model documentation for Generic Dynamic TEA prepared using SDM-DOC (*SDM-Doc*, 2021)

Process Model

Variable	Units	Equation	Description
Conversion to product	dmnl	0.5	Conversion of feedstock to product, developed from experiment or theory
Flow of Reactant 1 relative to key material	1	1	Flow rate of Reactant 1 relative to the key material flow, developed form experiment or theory
Flow of Reactant 2 relative to key material	1	2	Flow rate of Reactant 2 relative to the key material flow, developed form experiment or theory
Key Material Flow	L/hr	1000	Flow rate of the key material, an assumption based on experiments or theory
Product Flow	L/hr	(Key Material Flow+Reactant 1 Flow+Reactant 2 Flow)*Conversion to product	Flow rate of the product, based on the total flow and conversion
Reactant 1 Flow	L/hr	Key Material Flow*Flow of Reactant 1 relative to key material	flow rate of the reactant
Reactant 2 Flow	L/hr	Flow of Reactant 2 relative to key material*Key Material Flow	flow rate of the reactant
Waste Flow	L/hr	(Key Material Flow+Reactant 1 Flow+Reactant 2 Flow)*(1-Conversion to product)	Waste flow based on the remaining flow in after conversion of flow to product

Equipment Sizing

Variable	Units	Equation	Description
Heat capacity of mixture	J/(L*K)	1	Heat capacity of the mixture as used in the heater load calculation
Heater size	J/hr	(Key Material Flow+Reactant 1 Flow+Reactant 2 Flow)*Heat capacity of mixture*Temp increase Needed	Heater sizing based on the material flow, heat capacity and needed temperature increase
Key Material Pump Power	kW	Key Material Flow/L to cubic meters*Pump head*Key Material SG/(367*pump eff)*Power unit conversion	Calculation of pumping powerSource: https://engineeringunits.com/pump-power-calculator/
Key Material SG	dmnl	1	Specific gravity of key material, used for pump sizing
L to cubic meters	L/m3	1000	Unit conversion of L to cubic meters
Power unit conversion	kW/(m3*m/hr)	1	Conversion of the power units for the pump scaling
pump eff	dmnl	0.6	Pump eff., assumed
Pump head	m	100	Pressure head needed for the pumps, assumed.
Reactant 1 Pump Power	kW	Reactant 1 Flow/L to cubic meters*Pump head*Reactant 1 SG/(367*pump eff)*Power unit conversion	pump power calc for the flow of reactant 1Source: https://engineeringunits.com/pump-power-calculator/
Reactant 1 SG	dmnl	2	Specific gravity of the reactant used for pump sizing

Reactant 2 Pump Power	kW	Reactant 2 Flow/L to cubic meters*Pump head*Reactant 2 SG/(367*pump eff)*Power unit conversion	pump power calculation Source: https://engineeringunits.com/pump-power-calculator/
Reactant 2 SG	dmnl	3	Specific gravity of reactant 2, used for pump sizing
Residence Time Needed	hr	1	Residence time needed to achieve reaction coversion, developed from experiment or theory
Temp increase Needed	K	100	temperature increase needed for the reaction, used to size the heater
Vessel volume	L	(Key Material Flow+Reactant 1 Flow+Reactant 2 Flow)*Residence Time Needed	volume of a vessel needed based on the material flow and the residence time needed to reach the conversion

Capex

Variable	Units	Equation	Description
Blended Scaling exponent	dmnl	Scaling exponent Lookup(Vessel Scaling Ratio)	Scaling exponent based on lookup from Burk, 2018
Buildings	dmnl	0.1	Building cost factor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Construction Expenses	dmnl	0.41	Factor used for construction expenses Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Contingency	dmnl	0.44	Factor used for contingency Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Contractor's Fee	dmnl	0.22	Factor for contractor fee's Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Delivered Equipment Cost	$	Vessel Cost+Key Material Pump Cost	Sum of the equipment costs
Electrical systems	dmnl	0.11	Factor for electrical system costs Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Engineering and Supervision	dmnl	0.33	Factor for engineering and supervision costs Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.

Equipment Installation	dmnl	0.47	Factor for equipment installation costsSource: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Fixed-Capital investment	$	Total Direct Plant Cost+ Indirect Costs	Fixed capital investment as sum of direct plant costs and indirect costsSource: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Indirect Costs	$	Delivered Equipment Cost*(Construction Expenses+Contingency+Contractor's Fee+Engineering and Supervision+Legal Expenses)	Total indirect costs based on the delivered equipment costs and the relevant factors Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Instrumentation and Controls	dmnl	0.36	Factor for instrumentation and controls Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Key Material Pump Cost	$	Known Pump Cost*(Key Material Pump Scaling ratio)^Pump Scaling Exponent	Scaling for pump cost based on known pump cost scaling ratio and exponent Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Key Material Pump Scaling ratio	1	Key Material Pump Power/Known Pump power	Scaling ratio for the pump cost
Known Pump Cost	$	100	Known pump cost, from research
Known Pump power	kW	1	Know pump power, used for scaling
Known Vessel Cost	$	100	known vessel cost, from research or past projects
Known Vessel Volume	L	100	Known vessel volume used for cost scaling
Legal Expenses	dmnl	0.04	Legal expense factor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Piping	dmnl	0.68	Piping cost factor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.

Pump Scaling Exponent	dmnl	0.6	Pump scaling exponent Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Scaling exponent Lookup	dmnl	Scaling exponent Lookup([(0,0)-(10,10)],(0.001,0.2),(0.01,0.25),(0.1,0.4),(1,0.55),(10,0.7),(100,0.75),(1000,0.85))	From Burk - 2019 - Applying Scaling Laws in Process Engineering.pdf
Service Facilities	dmnl	0.7	factor for service facilities Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Total Direct Plant Cost	$	Delivered Equipment Cost*(Buildings+Electrical systems+Equipment Installation+Instrumentation and Controls+Piping+Service Facilities+Yard Improvements)	Calculation of direct plant cost based on the equipment cost and other factors: Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Vessel Cost	$	Known Vessel Cost*(Vessel Scaling Ratio)^Blended Scaling exponent	Scaled cost based on vessel scaling ratio and the scaling exponent
Vessel Scaling Ratio	1	Vessel volume/Known Vessel Volume	Scaling ratio of the vessel based on the known vessel volume
working capital	dmnl	0.15	Working capital factor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Yard Improvements	dmnl	0.1	Factor yard improvements Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.

OPEX

Variable	Units	Equation	Description
Admin Cost	$/hr	(Operating Labor Cost+Direct Supervisor and clerical labor Cost+Maintenance and repair cost)*Admin Cost factor	Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Admin Cost factor	dmnl	0.1	Example cost factor for admin costsSource: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003).

			Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Cost per operator	$/hr/person	75	Estimated hourly rate for a plant operator Source: Assumption
Depreciation	$/hr	Depreciation Factor*Total Capital investment	Calculation of deprecation costs based on total capital investment and the depreciation factor
Depreciation Factor	1/hr	0.05	Factor for depreciation Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Direct Manufacturing Costs	$/hr	Raw material cost+Waste treatment cost+Operating Labor Cost+Direct Supervisor and clerical labor Cost+Maintenance and repair cost+Operating Supply Cost+Lab Charges	Calculation of direct manufacturing costs Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Direct Supervisor and clerical labor Cost	$/hr	Operating Labor Cost*Direct Supervisor and clerical labor factor	calculation of the supervisor costs based on operating labor cost and a factor for supervisor and clerical labor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Direct Supervisor and clerical labor factor	dmnl	0.1	Factor from direct supervisor and clerical labor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Distribution and Sales Factor	dmnl	0.2	Factor for distribution and sales costs Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Fixed Manufacturing Costs	$/hr	Depreciation+Local Taxes and Insurance cost+Plant overhead cost	The fixed manuf. costs based on depreciation, taxes/insurance, and plant overheadSource: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
General Manufacturing Costs	$/hr	Admin Cost	General admin cost Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Key Material Cost	$/hr	Key Material Flow*Key Material Cost per unit	Total cost for the key material based on the flow and cost per unit of the material
Key Material Cost per unit	$/L	0.1	Cost per unit of the key material, source would be market research
Lab charge factor	dmnl	0.1	Factor for lab work Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Lab Charges	$/hr	Lab charge factor*Operating Labor Cost	cost of lab work Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Local Taxes and Insurance cost	$/hr	Total Capital investment*Local Taxes and Insurance Factor	Cost calc for the taxes and insurance: Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Local Taxes and Insurance Factor	1/hr	0.035	Factor for local taxes and insurance Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Maintenance and repair cost	$/hr	Total Capital investment*Maintenance and repair factor	total cost of maint and repair based on the factor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Maintenance and repair factor	1/hr	0.001	Factor for maint and repairs Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003).

			Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Operating Labor Cost	$/hr	Cost per operator*Operators needed	Operating labor based on cost per operator and the quantity of people needed
Operating Supplies factor	dmnl	0.02	Factor for operating supplies Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Operating Supply Cost	$/hr	Operating Supplies factor*Maintenance and repair cost	Operating supply costSouce: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Operators needed	people	5	Number of people needed to operate the plant
Partial cost of manufacturing	$/hr	Direct Manufacturing Costs Fixed Manufacturing Costs+General Manufacturing Costs	part of the cost of manuf.Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Patent and Royalty Factor	dmnl	0.05	Patent and Royalty factor: Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Plant overhead cost	$/hr	(Operating Labor Cost+Direct Supervisor and clerical labor Cost+Maintenance and repair cost)*Plant overhead Factor	calculation of plant overhead costs based on the various costs and factor Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Plant overhead Factor	dmnl	0.1	factor for plant overhead Source Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Raw material cost	$/hr	Key Material Cost+Reactant 1 Cost+Reactant 2 Cost	total cost for all reactants
Reactant 1 Cost	$/hr	Reactant 1 cost per unit*Reactant 1 Flow	total cost of reactant based on flow of reactant and cost per unit
Reactant 1 cost per unit	$/L	0.1	Cost per unit of reactant 1
Reactant 2 Cost	$/hr	Reactant 2 cost per unit*Reactant 2 Flow	cost of reactant 2 based on reactant flow and cost of the reactant
Reactant 2 cost per unit	$/L	0.1	Cost per unit of reactant 2, market research as a source
research and development factor	dmnl	0.2	Factor for R&D costs Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Total Capital investment	$	Fixed-Capital investment*(1+working capital)	Total capital based on the fixed capital and the working capital Source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Total operating costs	$/hr	Partial cost of manufacturing*(1+Distribution and Sales Factor+Patent and Royalty Factor+research and development factor)	Combination of all operating costs into a total operating cost per hour
Waste treatment cost	$/hr	Waste Flow*Waste Treatment cost per unit	total waste treatment costs based on cost to treat the waste and the flow and cost per unit to treat
Waste Treatment cost per unit	$/L	0.1	waste treatment cost per unit of waste flow, developed from research other assumed

Economic Metrics

Variable	Units	Equation	Description
amortized capex	$/year	(Total Capital investment*(interest rate/compounding periods in a year))/(1-(1+(interest rate/compounding periods in a year)^(-years amortized*compounding periods in a year)))/years amortized	Calculation of amortized costs to be used in profit estimates
compounding periods in a year	1/year	1	Compound rate Assumption
Costs	$/year	Total operating costs*Operating hours per year	Calculation of costs per year based on costs per hour and operating hours per year
Costs including annualized capex	$/year	amortized capex+Total operating costs*Operating hours per year	Addition of capex amortized to the annual costs
fiscal period	year	1	the fiscal period used for calculations
initial investment time	year	0	Time used for when the investment occurs, 0 assumes at the beginning of the simulation
interest rate	1/year	0.1	Interest rate used for financial calculations
IRR	1	INTERNAL RATE OF RETURN(net cash flow, fiscal period,-Total Capital investment,initial investment time)	Calculation of the IRR
net cash flow	$/year	Revenue-Costs	Net cash flow calculation
NPVe relative to initial time	$	NPVE(net cash flow, interest rate,-Total Capital investment,1)	NPV calc that matches the NPV calc in excel
Operating hours per year	hr/year	8400	operating hours per year for the plant
Payback period	year	Total Capital investment/net cash flow	Calculation of payback period
Profit at Specified year	$	SAMPLE IF TRUE(Time=Year to evaluate ROI,Profit less capital costs,0)	Variable to show the profit at a specified year
Profit less capital costs	$	Revenue-Costs0.0	Accumulation of the profit
Profit with annualized capital costs	$	Revenue Duplicate-Costs including annualized capex0.0	Accumulation of the profit
Revenue	$/year	Product Income*Operating hours per year	total revenue based on income per hour and operating hours per year
Revenue Duplicate	$/year	Product Income*Operating hours per year	Second revenue for second profit calculation
ROI at 20 years	dmnl	(Profit at Specified year-Total Capital investment)/Total Capital investment	Calculation of the ROI
Year to evaluate ROI	year	20	Year at which ROI is evaluated
years amortized	year	20	years over which the capex is amortized

APPENDIX C

Project Model

Variable	Units	Equation	Description
additional cost due from project model	$	total capex labor cost-labor costs for process project	the amount of added project cost over the plan due to project model
Average Productivity	Task/(People*Year)	IF THEN ELSE(Cumulative Effort Expended>0,Work Believed to Be Done/Cumulative Effort Expended, Normal Productivity)	Calculated average productivity over time
Average Task Duration	Year	0.0833	8 months, estimated, can be changed based on type of project
Change in Staff	People/Year	Switch For Indicated Staff*(Indicated Staff-Staff)/Time to Change Staff	Switch to prevent the hiring of people if that is a limitation
Cumulative Effort Expended	Person*Year	Effort Expended,0.0	Accumulation of the amount of person-years expended
Cumulative Work Done	Tasks	Rate of Doing Work,0.0	Accumulation of the tasks worked on
Design and Engineering Costs	$	Total Direct Cost*Design and Engineering Factor	Cost from Capex calculation
Design and Engineering Factor	dmnl	0.35	fee for engineering and administrative, source: Turton, R., Vailie, R., Whiting, W., & Shaeiwitz, J. (2003). Analysis, Synthesis, and Design of Chemical Processes (2nd ed.). Prentice Hall.
Effect of Work Progress	Dimensionless	Table for Effect of Work Progress(Fraction Really Complete)	Effect of work available based on progress
Effect on Productivity from Available Tasks	Dimensionless	IF THEN ELSE(Project Finished Switch=0,1,MIN(1,Maximum Work Rate/Potential Work Rate))	Change in productivity based on tasks available
Effort Expended	People	Staff*Project Finished Switch	the flow of effort used for cumulative effort expended
Error Fraction	fraction	MIN(1,(Normal Error Fraction+Incremental Errors from Undiscovered Rework))	Calculation of the error faction used for rework creation
Estimated Effort Remaining	People*Year	Project Finished Switch*Work to Do/Average Productivity	Estimate of the people-years remaining based on the average productivity
factor of labor relative to materials	dmnl	0.3	Factor to estimate fraction of the project cost that is labor https://www.botkeeper.com/blog/construction-labor-cost-percent
Fraction of Tasks Available to Work On Given Progress	fraction	Table For Fraction of Tasks to Work On Given Progress(Fraction Perceived to be Complete)	What work can be worked on given progress
Fraction Perceived to be Complete	fraction	Work Believed to Be Done/Initial Work to Do	What fraction of work seems like it has been done
Fraction Really Complete	fraction	Work Done/Initial Work to Do	What work is actually complete
Fraction Work Done	fraction	IF THEN ELSE(Work Believed to Be Done=0,0,Undiscovered Rework/Work Believed to Be Done)	Fraction of work that has errors in it

Containing Errors			
Incremental Errors from Undiscovered Rework	fraction	(1-Normal Error Fraction)*Table for Fraction of Undiscovered Errors Incorporated(Fraction Work Done Containing Errors)*Sensitivity of Incremental Errors to Past Errors	Added errors based on doing work with undiscovered rework
Indicated Staff	People	Estimated Effort Remaining/Time Remaining	How many staff are needed based on how much work is remaining and how much time is remaining
Initial Work to Do	Tasks	8	Estimate of tasks for the total project, can be changed based on specifics of project
labor burden per hour	$/Person/hr	100	Estimate of the cost per hour of labor for the project
labor cost ratio		total capex labor cost/labor costs for process project	Metric of what fraction of the project is labor cost
labor costs for process project	$	Total Direct Cost*factor of labor relative to materials+Design and Engineering Costs	Estimate of the labor cost for the project
Max Work Rate at Project End	Tasks/Year	Work to Do/Minimum Time to Perform a Task	Max work rate that can happen at the end of the project
Maximum Time to Discover Rework	Year	0.5	Max time it takes for rework to be discovered
Maximum Work Rate	Task/Year	MIN(Maximum Work Rate Based on Tasks Available,Max Work Rate at Project End)	Picking the max work rate based on tasks available and the rate at the end of the project
Maximum Work Rate Based on Tasks Available	Tasks/Year	IF THEN ELSE(Precedence Switch=1,Tasks Available to Work on/Average Task Duration,1000)	Sets the max work rate based on the how many task there are to work on and the average duration for the tasks
Minimum Time to Discover Rework	Year	0.125/12	Shortest time to discover reworking
Minimum Time to Finish Work	Year	0.08333	Shortest time the project can be finished in once over schedule
Minimum Time to Perform a Task	Year	0.08333	Shortest time a tasks
months per year	Month/Year	12	Unit conversion for months per year
Normal Error Fraction	fraction	0.25	Starting estimate of error fraction, Nominal rate as shown in Lyneis, 2007
Normal Productivity	Task/(Year*Person)	Initial Work to Do/(total people per project*planned project time frame)	Calculation of planned productivity based on the work to do, the labor planned for the project and the estimated project time frame
Normal Staff	People	total people per project	Labor estimated for the project
operating hours per year	hr/Year	24*7*50	operating hours per year
planned project time frame	Year	1	Planned timeframe the construction project will take
Potential Work Rate	Tasks/Year	Staff*Normal Productivity	Rate work can be done based on the number of people and the normal productivity
Precedence Switch	Dimensionless	1	Switch to turn off feedback effects from task precedence
Productivity	Task/	Normal Productivity*Effect on Productivity from Available Tasks	Normal productivity as adjusted by productivity effects

	(Person * Year)		
Project Finished Switch	Dimensionless	IF THEN ELSE(Work Done>Initial Work to Do*0.99,0,1)	Switch to stop behavior once project is done
Rate of Doing Work	Task/Year	Rework Generation+Work Done Correctly	Total rate of work completion
Rework Discovery	Task/Year	Undiscovered Rework/Time to Discover Rework	Rate of rework being discovered
Rework Generation	Task/Year	Error Fraction*Work Accomplishment	Rate at which rework is generated
Scheduled Completion Date	Year	planned project time frame	Ideal project time frame
Sensitivity of Incremental Errors to Past Errors	Dimensionless	1	Sensitivity factor for how sensitive the project is to errors on past work
Staff	People	Change in Staff, Normal Staff	Accumulation of staff with initial value of normal staff
Staff for Output	People	Staff*Project Finished Switch	Display variable of staff
Switch For Indicated Staff	Dimensionless	1	Switch to allow the change of staff
Table for Effect of Work Progress	Dimensionless	Table for Effect of Work Progress([(0,0)-(1,1)],(0,1),(0.1,1),(0.2,1),(0.3,1),(0.4,1),(0.5,0.9),(0.6,0.75),(0.7,0.5),(0.8,0.25),(0.9,0.1),(1,0))	Lookup table for effect of work progress on rework rate of discovery
Table For Fraction of Tasks to Work On Given Progress	fraction	Table For Fraction of Tasks to Work On Given Progress([(0,0)-(1,1)],(0,0.1),(0.1,0.2),(0.2,0.3),(0.3,0.4),(0.4,0.5),(0.5,0.6),(0.6,0.7),(0.7,0.8),(0.8,0.9),(0.9,1),(1,1))	Table for what fraction of work can be worked on given progress
Table for Fraction of Undiscovered Errors Incorporated	Dimensionless	Table for Fraction of Undiscovered Errors Incorporated([(0,0)-(1,10)],(0,0),(0.1,0.1),(0.2,0.2),(0.3,0.3),(0.4,0.4),(0.5,0.5),(0.6,0.6),(0.7,0.7),(0.8,0.8),(0.9,0.9),(1,1))	Table for how many errors get incorporated into future work
Tasks Available to Work on	Tasks	Max(0,Total Tasks That Could Be Worked On-Work Believed to Be Done)	Tasks that are not complete yet
Time Remaining	Year	Max(Minimum Time to Finish Work,Scheduled Completion Date-Time)	Calculation of time remaining in the project
Time to Change Staff	Year	0.0833	1 month
Time to Discover Rework	Year	Maximum Time to Discover Rework*Effect of Work Progress+(1-Effect of Work Progress)*Minimum Time to Discover Rework	Calculation of time to discovery rework between the min and max time as altered based on the lookup table from work progress
total capex labor cost	$	Cumulative Effort Expended*hours per month per person*labor burden per hour	Estimate of the total cost of the labor based on labor expended
Total Direct Cost	$	Mechanical Equipment Costs+Building Costs+Civil Cost+Installation Cost+Lagging and Paint Cost+Piping Platework, Ductwork Cost+Site Electric and Controls Cost+Site work and Landscaping Cost	Subtotal for direct costs
total people per project	Person	labor costs for process project/labor burden per hour/operating hours per year/planned project time frame	Calculation of the people needed for the project based on the estimated labor cost and planned project timeframe
Total Tasks That Could Be Worked On	Tasks	Initial Work to Do*Fraction of Tasks Available to Work On Given Progress	Tasks that can be worked on given progress
Undiscovered Rework	Task	Rework Generation-Rework Discovery,0.0	The accumulation of undiscovered rework, initialized at 0 task

Work Accomplishment	Task/Year	Staff*Productivity*Project Finished Switch	Rate at which work gets done
Work Believed to Be Done	Tasks	Undiscovered Rework+Work Done	Work thought to be done
Work Done	Task	Work Done Correctly, 0.0	Accumulation of work done correctly, initialized at 0
Work Done Correctly	Task/Year	(1-Error Fraction)*Work Accomplishment	Fraction of work done correctly
Work to Do	Tasks	(Rework Discovery-Rework Generation)-Work Done Correctly,Initial Work to Do	Work that is known as being still to do, initialized at initial work to do

Pricing Model

Variable	Units	Equation	Description
additional Demand	t/Year/Year	Input demand development*Exogenous Demand	Flow of demand into the demand stock
amp	dmnl	4	Amplitude of production delay function
average prephase		0.5	Average fraction of initial pool that initialized the prephase production projects
Delta Supply Demand	t	(Exogenous Demand-Total Production Capacity)/Exogenous Demand	Relative deviation of supply and demand
dynamic growth factor	dmnl	0.04	Factor that increases the demand growth rate
Input demand development	1/Year	0.04*(1+dynamic growth factor)	Calculation of the demand growth based on a nominal growth of 4% and modified by the dynamic growth factor
Exogenous Demand	t/Year	additional Demand, Initial Demand	Accumulation of demand, initialized at a historical demand
Initial Demand	t/Year	210500	Historical demand used to initialize demand stack
Initial price equilibrium	$/t	7000	Historical initial price, assumed to be the price at equilibrium
Initial value project pool		Input demand development*Total Production Capacity*1.05	Total initial project pool
Investments in new production capacities	t/Year	IF THEN ELSE(Price Alteration Rate<0, Input demand development*0.5*(Total Production Capacity),((Price Alteration Rate/Price Level)*(Total Production Capacity)))	Initiates new production based on a difference in price alteration, if below 0 then it is half of the initial demand times the production capacity, otherwise it is the price alteration rate divided by the price times the current total production capacity.
new production capacities	t/(Year*Year)	Projects/time to bring projects online	Time for new production projects to come online
offset	years	5	Time offset of production delay function
Price Alteration Rate	$/t	Delta Supply Demand*Price Level*sens constant	Price alteration depending on the relative difference between supply and demand
Price Level	$/t	Price Alteration Rate, Initial price equilibrium	Price level initialized at equilibrium
Projects	t	Investments in new production capacities-new production capacities, Initial value project pool*average prephase	Accumulation of potential projects that are on online yet, initialized via the initial project pool times the average fraction of projects in the prephase

sens constant		1	Sensitivity to price constant used for calibration
time to bring projects online	Year	SIN(Time/width)*amp+offset	Delay function for projecting coming online
Total Productio n Capacity	t	new production capacities, Exogenous Demand	Online production capacity
width	dmnl	2.97	Width adjustment of the peaks in production delay function

Hiring Model

Variable	Units	Equation	Description
attrition	People/ Year	Experienced Personnel/average time at a job	Rate of people leaving the job
average time at a job	Year	5	Researched value of average years on the job https://www.rasmussen.edu/degrees/business/ blog/employee-tenure-trends/
average time to recruit	years	0.1	Estimate of the average time to recruit people
avg employee cost	$/Person /Year	82500	Average cost of people per year, assumed from REE TEA
Candidates	People	(recruiting-drop out)-hiring, 0.0	Accumulation of candidates, initialized at 0
drop out		(Candidates/time to vet candidates)*(1-ratio acceptable candidates)	Rate at which candidates drop out
Experienced Personnel	People	gaining experience-attrition, 0.0	Accumulation of experienced personnel, initialized at 0
fraction of new hires who leave	dmnl	0.75	Fraction of new hires who leave after being hiring, estimated
gaining experience	People/ Year	(New Hires/time to gain experience)*(1-fraction of new hires who leave)	Rate at which people gain experience
gap in labor	People	gap in labor spending/avg employee cost	Gap in desired labor converted to people
gap in labor spending	$/Year	Labor-hired labor cost	Gap in labor spending (desired labor minus hired labor)
hired labor	People	hired labor cost/avg employee cost	Hired labor converted to people
hired labor cost	$/Year	Workforce*avg employee cost	Cost of labor
hiring		(Candidates/time to vet candidates)*ratio acceptable candidates	Rate at which candidates are hiring
Labor	$/Year	1e+06	Target labor Costs from TEA OPEX
new hire attrition	People/ Year	(New Hires/time to gain experience)*(1-fraction of new hires who leave)	Rate at which new hires leave
New Hires	People	(hiring-gaining experience)-new hire attrition, 0.0	Accumulation of new hires, initialized at 0
ratio acceptable candidates	dmnl	0.25	fraction of candidates that are acceptable
recruiting	People/ Year	gap in labor/average time to recruit	Rate at which candidates are found
time to gain experience	Year	1.5	time to gain experience
time to vet candidates	Year	0.33	time to vet candidates
Workforce	People	Candidates+Experienced Personnel+New Hires	Total workforce of all types