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# THE DEVELOPMENT OF A MARITIME FREIGHT MODELING FRAMEWORK WITH AN APPLICATION IN LNG SHIPPING

## Ryan Pfeifer

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Supervisor:       Bjørn Egil Asbjørnslett, IMT

Norwegian University of Science and Technology
Department of Marine Technology

# MASTER THESIS

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**ABSTRACT:**

The dynamic, expansive, and integrated nature of global maritime freight transportation systems motivates the need for modeling tools that can effectively evaluate a highly diverse assortment of maritime freight systems and markets. This thesis presents the development and implementation of a generic maritime freight transportation model that can be used to analyze a wide variety of maritime freight transportation systems and problems. The model was implemented into an MS Excel VBA program tool as a means of demonstrating the capabilities and use of the generic model. This tool was then used in a case study involving LNG shipping. The objective of the case study was to assess the effects of the Panama Canal tariff on an emergent LNG trade between the Gulf of Mexico and the Asia-Pacific region. The case study and discussions show that the model provides a sufficient core framework for maritime transportation systems, but has weaknesses in stake holder definition and available data compatibility. The core functionality that allows the model to represent a wide variety of problem types is its ability to very specifically or broadly define the entities within a transport system.

**Keywords:**

**Freight Modeling**

**Maritime Transportation**

**LNG Shipping**

**Advisor:**

**Bjørn Egil Asbjørnslett**

# PREFACE

This Master Thesis is submitted in partial fulfillment of the requirements for the Master of Science degree in Marine Technology at the department of Marine Technology at the Norwegian University of Science and Technology (NTNU), in Trondheim, the spring of 2013. The topic of this thesis was originally proposed by Arnulf Hagen at DNV proNavis. The information provided by Arnulf Hagen served as a conceptual starting point –the work done to develop the generic model as presented was completed by the author of this paper.

The primary objective of this Master Thesis was to develop a generic model of maritime transport systems. The secondary objective of this work was to implement the model into a practical MS Excel VBA tool, and utilize the tool in a case study involving LNG shipping.

Ryan Pfeifer
Trondheim, 10/06/2013

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**SUMMARY**

The growing complexity of maritime freight transportation systems and increasing environmental concern have led to the demand for effective modeling tools that can be used to effectively and rapidly evaluate freight markets and freight transport solutions. Currently, freight transport models are purpose-built for specific problem scopes and definitions with little work done to create a unified framework for modeling maritime transport systems. The main motivation for a generic framework lie in the capability to model highly dynamic systems, and also the ability to model systems with a unified methodology that have highly diverse demand and supply profiles.

This thesis presents the development of a generic maritime freight model with the main objective of providing a core framework that can be used to represent a wide variety of maritime transport operation scenarios and problems. This thesis also presents the implementation of the developed generic modeling framework into a practical MS Excel VBA tool, and uses the tool in an LNG shipping case study.

Before the model development a model-oriented background in both maritime transportation and transportation modeling is presented as a means of developing the required knowledge to present a set of requirements for the generic model. The generic model was developed using the domain modeling technique which is a widely used method of establishing the concepts and relationships between the concepts within a problem domain scope.

The development of the domain model was performed in two major segments: demand modeling, and supply modeling. Each of the segments was composed of various domain model packages which wholly describe a freight transport system. Throughout the development of the domain model, discussion and explanation is given which focuses on how certain developments work to fulfill the requirements of the model. With the domain modeling complete, a cost analysis methodology is presented.

The fully developed domain model was implemented into an MS Excel VBA program as a means of demonstrating the practical implementation and use of the program. The implementation of the program is fully presented with descriptions of the functional objectives of the program, the data structure of the program, and the user interaction with the program. To show the use of the generic model within the tool, a case study is presented that

assesses the effect of Panama Canal pricing an en emergent LNG trade between the Gulf of Mexico and the Asia-Pacific region.

The thesis concludes with a discussion on the weaknesses of the generic model. Most notably the model development did not consider the types of data that were available for inclusion in the model. Also, issues arise with stake holder definition and the proper allocation of cost elements to the actors in the model.

The main conclusion of the thesis is that although the generic model lends itself to certain analyses, it provides a viable core framework for modeling maritime transportation systems. This stems mostly from the model's ability to generate feasible solutions based on either very specific or very board definitions of demand and supply variables.

# 1. INTRODUCTION

The growth of the global economy relies on and promotes the transportation of energy, raw material, and products within international trade networks. An increasing focus on environmental impacts, a growing sophistication and dynamic nature of supply chains, and a growing integration of transportation networks necessitates the use of transportation modeling and analysis decision support tools. These tools can be used to analyze freight transportation markets and to develop the most effective and efficient freight transportation solutions (Pendyala, 2). The dynamic, expansive, and integrated nature of global freight transport networks motive the need for a generic freight modeling framework that can be used to practically model a wide variety of freight transportation systems with a unified methodology.

Major efforts in developing practical transportation modeling tools have been centered on passenger transportation leaving state-of-the-practice of freight modeling unsatisfactory. This has largely been the result of the difficulties that lie in representing the decision making process in freight modeling, the lack of a modeling framework, and the scarcity of freight data (Pendyala, 2). Furthermore, supply chain structure change rapidly through either commodity market dynamics or through logistical and technological advancements making modeling techniques used in passenger transport unsatisfactory. In general, attempts to model freight transportation systems have been purpose-made and suited for a specific analysis type.

The aim of this research is to develop a generic maritime freight transportation model that is capable of modeling a wide variety of maritime transport systems, and also supports multiple transportation planning problem types. The secondary aim of this research is to implement the developed generic model into a practical and useful tool using Visual Basic for Applications (VBA) within Microsoft Excel. Another goal of this thesis is to demonstrate the use and capability of the developed tool in a case study that involves LNG shipping.

This paper is organized as follows. It will first present a background in intermodal freight transportation, maritime transportation, and freight transportation modeling. This will be followed by a discussion of the specific objectives and scope of the modeling framework. Once the objectives are established, the methodology used to develop the model will be presented as well as the system of symbolism and naming used. The development of the model will then be presented in two main packages: demand modeling of maritime transport, and supply modeling of maritime transport. This will be followed with a presentation of how

the cost of maritime supply is modeled and how the supply is match to demand. The model will then be applied to an LNG shipping analysis. Finally, there will be a discussion about the weaknesses and achievements of the generic model.

## 2. BACKGROUND

## 2.1 INTERMODAL FREIGHT TRANSPORTATION

Freight transportation is the movement of goods between two locations and often involves the combined use of more than one mode of transportation. These intermodal movements use two or more different modes of transportation, linked end-to-end, in order to move freight from a point of origin to a point of destination (Southworth). Freight transportation is carried out on a global intermodal network composed of various actors that demand and provide transportation services. These services include freight movement via airplane, truck, train, or ship, and transfer services to move cargo between the modes. There are also a variety of stakeholders including customers, service providers, and governments that have different interests and impacts on freight transportation networks and services. Complex relations also exist between the actors and the stakeholders involved. Therefore it is important to consider freight transportation as an integrated system (Crainic).

## 2.3 MARITIME TRANSPORTATION

Maritime transportation refers to freight transportation from and inland origin to an inland destination that includes the use of ocean shipping. Ocean shipping is the most utilized and efficient way to transport large volumes of cargo between continents and represents between 65% and 8% of total international trade (Christiansen). In general, the demand for maritime transportation can be described by the type of goods to be shipped, the type of packaging that the goods will be shipped in, and the size and frequency of the shipments. The supply of maritime transportation can be described by the inland and ocean transportation services and their vehicles. Figure 1 illustrates how the demand for maritime transportation is related to the supply. What is important to take away from this diagram in this study is that there are a variety of ways that a demand for maritime transportation can be fulfilled, independent of the origin and the destination of the demand.
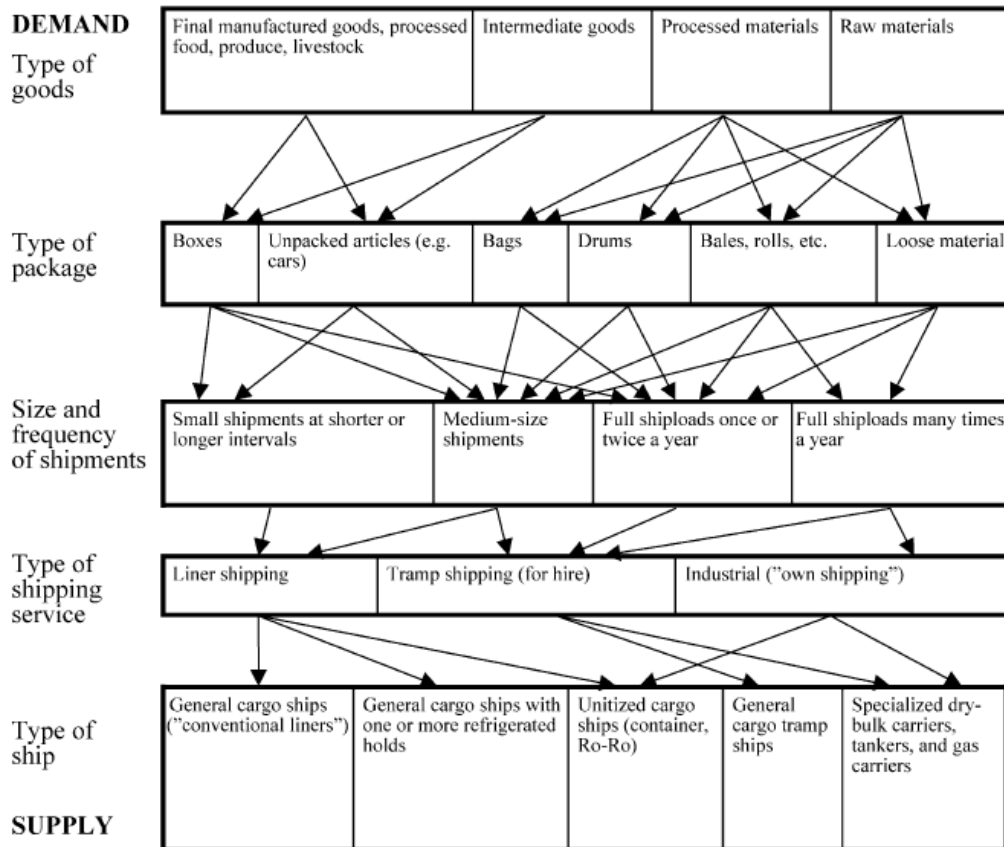
Figure 1: Supply and demand of maritime transportation (Christiansen)


### 2.3.1 Supply of Maritime Transportation

In this model, a specific instance of a maritime transport supply consists of three legs or segments when transporting freight from an inland origin to an inland destination. The first leg is the movement of the cargo from the inland origin to a port terminal where it can be transferred to a deep-sea vessel. The second leg is the ocean leg of the transport which moves the freight from the origin port terminal to the destination port terminal. The third leg of the operation is the freight movement from the destination port terminal to the inland destination. The inland legs of the transport operation are often referred to as the hinterland legs of the operation. Each of these segments requires the supply of a transportation service to accomplish the demanded cargo movement.

### 2.3.2 Demand for Maritime Transportation

In this model, a specific instance of a maritime transport demand consists of a physical description of the cargo, the origin and the destination of the cargo, the service level required

by the party that demanded the shipment, and the time span the shipment it to be completed in.

## 2.4 MODELING OF MARITIME TRANSPORTATION SYSTEMS

The intention of this section is to describe the general characteristics of freight transportation models in preparation to define the function requirements of the generic model.

A freight transportation system can be described as a set of entities and interactions between them that produce a demand for transportation and the provisions to supply transportation services to satisfy the demand (Zanjirani). The goal of a freight transportation model is to provide a means to effectively and efficiently represent these entities and interactions in an effort to facilitate models that can be used to represent and evaluate a transportation system as a whole. The main concepts that must be represented in a transportation model are the transport demand, the transport supply, the matching of supply and demand, and the decision criteria included in the model (Crainic). The following sections will discuss how these concepts can be modeled.

In general, the entities and interactions included in a freight transportation model must be specific to a problem scope and model objectives. This is because it is often not possible to directly model all of the influences, entities, and interactions that are connected to the problem.

### 2.4.1 Modeling Supply

The supply of maritime transportation can be modeled as in intermodal network of transport infrastructures (ports), and the services provided by them, and the multimodal services that operate between the facilities to move freight from an origin to a destination (Boilé). A model of maritime transport must be able to connect these facilities (origins, destinations, ports, hubs, etc…) with transportation networks on which the transport services act. The model must be able to include data that can describe the capacities and costs of the network facilities as well as their connections to the transportation networks. The model must also be able to include transportation network components associated with the transportation services such as travel distances, way point or hubs, and transit tariffs. Lastly, a transportation supply model must be able to describe the transportation services, and their associated capacities, and costs that act on the transportation networks between the facilities.

### 2.4.2 Modeling Demand

The goal of demand modeling is to represent the volumes of good that move between locations. The typical output of a demand model is an origin-demand matrix (*O-D* matrix) for each good being modeled that specifies the volume of goods to be moved from the origins to the destinations. The modeling of demand considers the economic activities of region including production, consumption, imports, and exports. *O-D* demand matrices can be built from national statistics and surveys of industrial sectors (Crainic).

Many freight models use aggregated demand data that doesn't include parcel-specific information. These models often only define the demand as a certain volume of a commodity that is to be moved from an origin to a destination. Disaggregate demand models include parcel-specific characteristics and the characteristics of the available supply alternatives to determine how the shipment of a commodity will take place. This can be illustrated by Figure 1 where a completely aggregate demand description would stop defining the demand at the top level. The descriptions added to the demand as you move down the figure lead to increasingly disaggregate descriptions. Figure 1 also shows that the level of disaggregation in the demand description is only as useful as the level of characterization of the supply alternatives.

### 2.4.3 Assigning Supply to Demand

The process of assigning the transportation supply to demand is often referred to as transportation network equilibrium. Transport network equilibrium is the problem of the network users (transport services), seeking to maximize or minimize an objective function (min cost, max profit, etc…) between their origin and the destination. The results of this equilibrium are predictions of the traffic flows on the network, the cargo flows on the network, and the performance measures of the transport operation like emissions and cost.

There are a variety of objective functions that can be used to assign supply to demand. Assignment methodologies vary depending on the perception of the user and representation of the actors within the model. In user optimization, the supply services are treated as individual description makers and act to benefit their own objective. The opposite approach is called system optimization where assignment decisions are made to optimize a single global variable (Boilé). The results produced by these simulations can be used to benchmark existing systems and run analyses to compare the effects of changes to the system. Such

analyses can study the effects of varying transport demands on traffic flows, canal tariffs, fuel prices, or terminal policy changes.

## 2.5 PLANNING LEVELS IN FREIGHT TRANSPORTATION

Apart from modeling the physical entities and interactions within a transportation system, there is a temporal aspect that must be considered. In general, there are three levels of planning associated with freight transportation systems: strategic, tactical, and operational.

### 6.3.1 Strategic Planning

Strategic planning is long term planning (>1year) concerning the design of a freight transportation network. Strategic planning involves physical the allocation of terminals, transshipment hubs, and other infrastructures that facilitate freight transportation. Strategic planning also includes decisions to expand transport capacity and changes to tariff policies. Strategic planning determines the general planning and trends of the transportation system in the long-term horizon. Strategic planning can take place at the regional, national, and international level (Zanjirani). The geographical scope of strategic planning is determined by the geographical scope of the transportation system as well as the scope and objective of the firm performing the planning. Strategic planning often demands tactical or even operational information creating an overlap between strategic and tactical and/or operational decisions (Christiansen).

### 6.3.2 Strategic Planning in Maritime Transportation

Strategic planning in maritime transportation covers a wide range issues from the design of a transportation service to the selection of contracts. The volatile and competitive nature of maritime transportation greatly complicates strategic decisions which often need to be based on market forecasts (Christiansen). Most strategic shipping decisions are on the supply side and include:

- Market selection
- Fleet size and mix
- Transportation system/service network design
- Maritime supply chain/maritime logistic system design
- Ship design

### 6.3.3 Tactical Planning

Tactical planning is medium-term planning that determines resource allocation within a freight transportation system in order to make it more effective or efficient. Medium-term planning can include carrier specifications and service type specifications. Medium-term planning is responsible for determining the entities that operate on the physical transportation network (Zanjirani). Tactical planning can take place across multiple modes of transportation and transshipment facilities or for only one mode of transportation depending on the type of service under consideration and the scope of the company performing the planning.

### 6.3.4 Tactical Planning in Maritime Transportation

Tactical planning in maritime transportation is focused on routing and scheduling of ships to meet a transport demand (Christiansen). Tactical planning problems include:

- Adjustments to fleet size and mix
- Fleet deployment (assigning ships to trades)
- Ships routing and scheduling
- Inventory ship routing
- Berth scheduling
- Crane scheduling
- Container yard management
- Container stowage planning
- Ship management
- Distribution of empty containers

Tactical planning problems: Service network design, traffic routing, terminal policies.

### 6.3.5 Operational Planning

Operational planning is short-term planning performed by the local and operational management. Operational planning includes scheduling and implementing carriers, freight services, crews, and maintenance activities. Operational planning must effectively and efficiently plan the routing and allocation of carrier to fulfill a demanded transport service (Zanjirani). Operational planning may also include the selection of transportation services to provide in order to return the most profit.

### 6.3.6 Operational Planning in Maritime Transportation

Operational planning in maritime transportation deals with situations when the operational environment is highly uncertain and dynamic or when decisions have only a short

term impact (single voyage) (Christiansen). Operational planning problems in maritime transportation include:

- Vessel speed selection
- Environmental routing concerning individual voyage legs
- Ship loading

## 3. REQUIREMENTS OF THE GENERIC MODEL

Now that a general presentation of maritime freight transportation and transportation modeling has been presented, the objectives and scope of the model can be laid out. As previously mentioned, the general objective of the generic model it to provide an effective and unified method of describing a wide variety of maritime freight movement scenarios while also supporting different planning problem types. Another general objective of the model is to incorporate only the vital entities and interactions and serve as a core framework for transport models. The point of this is to avoid developing a model that caters to a specific analysis type or trade.

Given these general objectives, and the background discussion, a set of requirement for the model was generated.

1. Support a practical level of disaggregation in the demand data input. The level of disaggregation should be sufficient enough to make decision-maker distinctions and to appropriately match the transport demand to a supply.

2. Support the concept of services, made up of vessels, fulfilling demand. The definition of the services must be compatible with the disaggregated demand description as a means of making the demand disaggregation useful in the supply-demand matching process.

3. In order to make the framework useful for a variety of transport analyses that may look at any of the main entities (ports, services, vessel types, cargoes, routes) of a transport system, the model should allow the very specific or broad definition of the entities involved in an analyses. For example, one analysis may be concerned with the flow of container through a specific port terminal, while another may be concerned with the flow of container vessels through a the Suez Canal. The first case requires a specific definition of the port and the cargo type and a broad definition of the other variables in the model such as the ports of origin of the containers. The second case requires a specific definition of the vessel routing and

the vessel type, and a broad definition of all other variables (origin and destination ports).

4. Infrastructures in the model should be identifiable by user specific regions as a means of contributing to the functionality of the third objective. This will allow a model to include all infrastructures of a given type and within a given region in an analysis. This is useful in modeling all cargo flows between two regions or on a certain route.

5. The model should provide a unified method for evaluating the cost of any maritime transport operation.

6. The model should support problems over all planning levels.

7. The model should cater to the systematic generation and evaluation of a large number of transport solution alternatives and provide a basis for a software solution and the inclusion of supply-demand matching and route optimization modules.

# 4. METHODOLOGY

## 4.1 GENERIC MODEL DEVELOPMENT

The development of the generic model is presented in four major segments: model overview, demand modeling framework, supply modeling framework, and cost modeling.

The model overview will demonstrate how the model packages interact to model a full scenario. The demand modeling and supply modeling framework, which represent the core of the model, were developed using domain modeling techniques, symbolism and naming schemes. The presentation of the development of the supply and demand domain models is focused on demonstrating to the reader how the requirements of the generic model are fulfilled. This includes both a discussion about the transport system elements that need to be incorporated into the model and why they are needed. The discussion of the transport elements that need to be incorporated into the model is based heavily on Martin Stopford's *Maritime Transportation* which is a highly acclaimed reference in the realm of maritime transportation (Stopford).

The supply cost module was developed to utilize the generic demand and supply models as inputs to a cost calculation. This development it presented mainly as discussion, but will be implemented into the VBA tool.

## 4.2 DOMAIN MODELING

A domain model establishes the concepts within the domain or scope of a problem, as well as the relationships between the concepts. A domain model also established the vocabulary of the problem domain. A domain model is an object oriented system that consists of classes and associations between them (Kienzle).

### 4.2.1 Class

A class is a model element that represents a physical thing or concept that can be distinctly identified. A class also identifies the attributes that objects within the class will have. For example, a class can be "Ship" with attributes like speed and fuel consumption. A specific instance of a class is an object. The objects created by the "Ship" class would be specific ships with unique names. The graphical representation of a *class* is a rectangular box with two sections as shown in Figure 2. The top section contains the *class name,* and the lower section contains the *attributes* of the objects in the (Kienzle). Classes with the same name that appear in different packages are the same class.
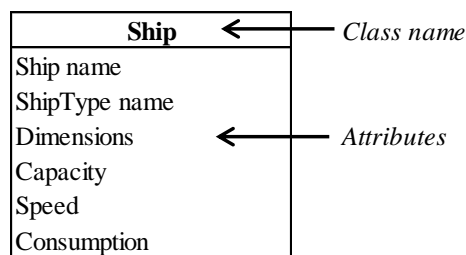


Figure 2: Physical representation of a class

### 4.2.2 Associations

An association models the relationship between two classes whose objects are involved in the relationship. The graphical representation of an *association* is a line that adjoins the classes involved in the relationship as shown in Figure 3. The name of the association is place on the line and an arrow indicates how to read the association relationship. In most cases in this model, the relationship between classes is a two-way so there is no arrow included (Kienzle).
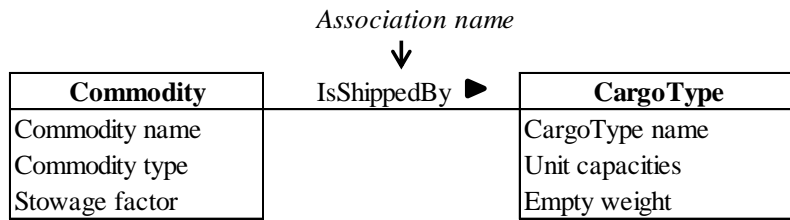
Figure 3: Physical representation of an association

## 4.2.3 Higher Order Associations

Higher order associations are used to model the relationship between one or more classes whose objects are involved in the relationship. The graphical representation of a higher order *association* is a diamond shape that adjoins the related classes with lines as shown in Figure 4. The name of a higher order association is placed above the diamond shape, and unlike the binary association, the name is typically a noun that describes the multi-dimensional relationship (Kienzle).
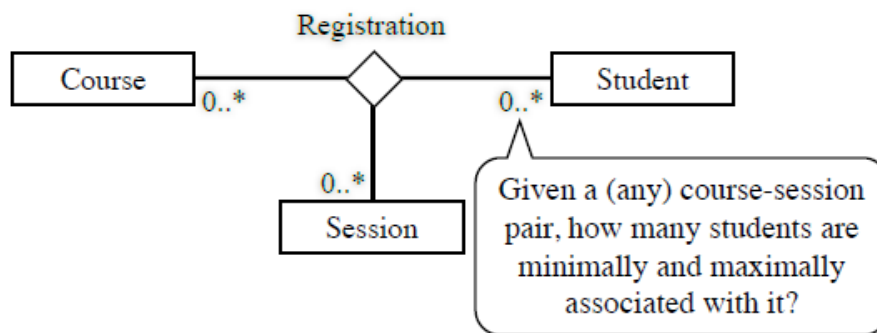


Figure 4: Physical representation of a higher order association (Kienzle)

## 4.2.4 Association Class

An association class is an association that connects classes and also stores attributes that describe the relationship between the objects in the classes it links (Kienzle). For example, the route class would be an association class because it stores attributes (route data) between an export port class object and an import port class object. The graphical representation of an association class is a dotted line that is attached to an association as shown in Figure 5.
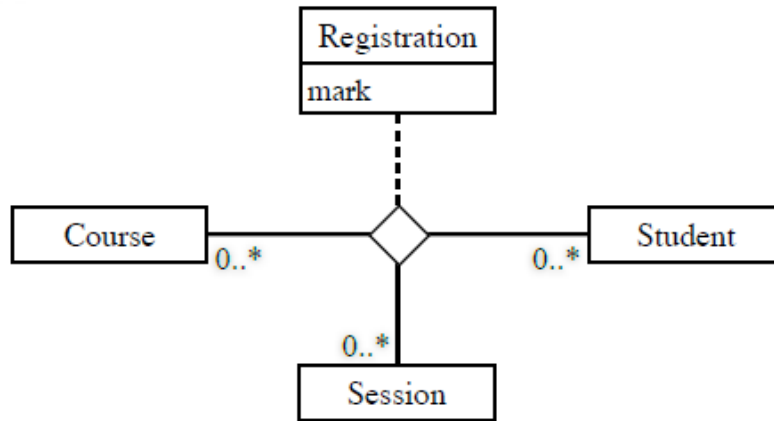
Figure 5: Physical representation of an association class (Kienzle)

## 5. GENERIC MODEL OVERVIEW

The underlying framework of the model is composed of three major packages: the demand package, the supply package, and the cost analysis package. Figure 6 shows a very general representation of the framework and the information that is passes between the modules. The following points briefly describe the main purposes of each package.

- **Freight transport demand modeling package**: The purpose of this module is to represent the demand for a transport operation. This is accomplished by defining the cargo to be traded, the volumes and time span of the trade, and the require transport service.

- **Freight transport supply modeling package:** The purpose of this modules is to represent the supply of freight transportation that fulfills the demands as they are defined in the demand module. The supply module models a variety of methods of carrying-out a demanded transport operation. The supply module defines the routing of the trade, the modes and services used in the operation, and the various parameters needed to calculate the performance of the operation.

- **Cost analysis package:** The purpose of this module is to take the description of the transport operation as defined by the previous modules and calculate the desired performance parameters of the transport operation.
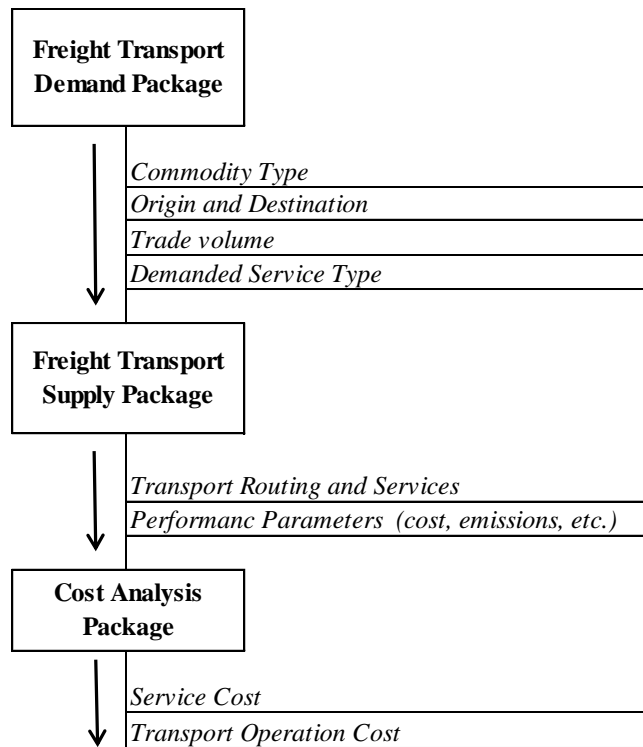
Figure 6: Conceptual modeling framework.

## 6. DEMAND MODELING DEVELOPMENT

The demand for maritime freight transportation can be generally characterized by the type of cargo to be shipped, the origin and destination points of the cargo movement, and the amount of cargo to be shipped in a given certain time-frame. The following sections will further define each of these aspects of sea transport demand and also develop a domain model package that can effectively represent the demand for freight transport within a generic sea transport model. The development will include discussion on how certain characteristics of the generic model fulfill the requirements of the generic model as a whole.

### 6.1 CARGO MODELING

As discussed, a freight transportation model may require the functionality for disaggregated demand descriptions. Therefore, a generic model of a demanded freight movement must include the ability to provide a sufficient description (beyond commodity description) of the type of cargo to be shipped.

Cargo definition is not just about the commodity, because the same commodity can be shipped in different ways (Stopford, 572). For example, LNG can be shipped in bulk via

LNG carrier or in smaller parcels via LNG containers. In this model, cargo types are to be defined by the commodity, the size of the cargo shipment, and how the commodity is physically packed when it is shipped. Another importation distinction related to the cargo is the level of service demanded by the shipper. The following will discuss each of these features of maritime cargoes and develop a cargo demand model.

### 6.1.1 Cargo Domain Model Description

Before the cargo domain model classes and associations are developed and discussed, it is useful to make a general presentation of the complete cargo domain model. Figure 7 shows the cargo domain model. There are two primary functions of this domain model:

1. Store the transport activity parameters (cost, capacities) each of the cargo related objects.
2. Provide a means of generating all feasible cargo solutions starting from any class in the model to fulfill requirement 3 of the model.

The following will present an example of how the domain model defines a feasible cargo. Starting with the "Commodity" class, a commodity name is selected which, generated all feasible "Cargo Type" objects. The "Commodity" and "Cargo Type" objects selections then generate all feasible "Service Type", "Ship Type", and "Inland Mode" objects. Object selection in each of these classes can then be made to fully define a cargo.

Another example will now be given starting from the "Ship Type" class to demonstrate that feasible cargo solutions can be defined starting from any class in the model. Starting with the "Ship Type" class, a ship type object is selected which generates all feasible commodity and cargo type objects. Note that the association also links the "Commodity" and "Cargo Type" classes meaning the feasible objects in the classes are also governed by this association. The "Commodity" and "Cargo Type" objects selections then generate all feasible "Service Type", and "Inland Mode" objects. Objects selections in each of these classes can then be made to fully define a cargo.
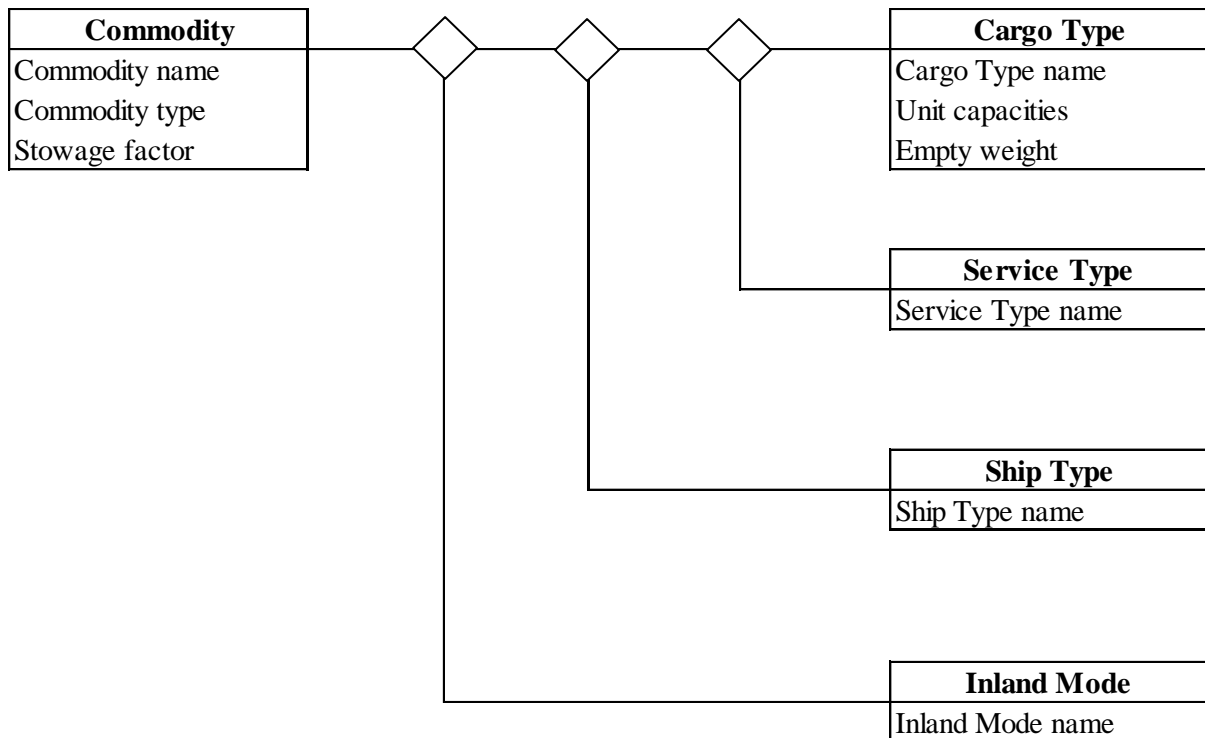
Figure 7: Cargo domain model

The following sections will describe the development of each of the classes in the cargo domain model.

### 6.1.2 Commodity Class

The global sea trade consists of many different commodities including raw materials, agricultural products, and consumer goods. Analyzing sea trade deals heavily with forecasting developments within these commodity trades. Often these developments are interrelated through certain industries like energy trades, and metal industry trades (Stopford, 56). Therefore, the "Commodity" class contains the "Commodity type" attribute.

Although the role of a commodity in the context of the world economy is important from a broad analysis perspective, the physical properties of the commodity are most important when modeling a specific sea transport operation as is the case with a specific instance of the cargo domain model. The only essential commodity property in the context of modeling a physical transport operation is the stowage factor of the commodity. Stowage factor is, "the volume of hold space in cubic meters occupied by a tonne or cargo" (Stopford, 575). This allows the model to determine either the volume or the weight of the cargo to be shipped and hence the size of the ship needed for the transport. Therefore, the "Commodity" must contain the "Stowage factor" attribute.

Other commodity properties may impose certain transportation restrictions, as is the case with certain hazardous or special chemical cargoes. However, there is no need to list them as attributes of the commodity class in this model. This is because the model will handle such associations by only associating these commodities with the required shipping method (physical shipping unit and vehicle type).

### 6.1.3 Cargo Type Class

A 'parcel' is an individual consignment of cargo. Parcel sizes vary greatly across all commodities shipped by sea. For example, a parcel can be an entire shipload of a bulk commodity (iron ore) or 100 cases or wine for a wholesaler. Every traded commodity has a parcel size distribution (PSD), which describes the parcel sizes that the commodity is typically traded in. The PSD for a commodity is impacted by three main factors: the stock levels of the commodity held by the end user, the vessel size restrictions of the loading and discharging terminals, and the economies of scale related savings (Stopford, 59).

The parcel size of a traded commodity is important because it helps determine what type of ship and shipping service will be used to transport it. A major division of how a commodity is shipped, based on its parcel size, is bulk cargo and general cargo. Bulk cargo consists of parcels that are big enough to fill an entire ship or an entire hold of a ship while general cargo consists of small consignments that are packed with other cargo when transported (Stopford).

Commodities are often traded in ranging parcel sizes, meaning that the commodity alone cannot determine the type of ship and service that should carry-out a transport operation. Therefore, for a given transport operation, it is necessary to define the parcel size with the goal of determining the type of the ship the cargo should be transported in and the type of shipping service to carry out the movement. This means that a model of parcel size must cater to the selection of a vessel type and shipping service.

For the purposes of this generic freight model, parcels are classified into two main groups: bulk cargo parcels, and general cargo parcels. As will become apparent, this parcel size distinction caters well to the selection of a ship type and shipping service to carry out the transport activity.

- *Bulk cargo parcel*: Any individual parcel big enough to fill a ship or hold
- *General cargo parcel*: Any individual parcel too small to fill a ship or hold

Another distinction that determines the type of vessel to carry out a transport operation is the physical units that the cargo is transported in. Both bulk cargo parcels and general cargo parcels are shipped in a variety of physical units. Figure 8 shows the different basic physical units that maritime cargo is shipped by. As shown in the figure, the physical unit in which cargo is shipped is impacted by both the commodity (liquid, homogeneous, etc…) being shipped and the parcel size of the shipment.

| Parcel size | Phycial unit | Comments |
|---|---|---|
| Bulk cargo parcels | Dry bulk cargo | Loose homogeneous cargo in parcels that are at least the size of a hold on a ship. (e.i. iron ore, grain, coal) |
| | Liquid bulk cargo | Loose homogeneous liquid cargoes that are at least the size of a hold on a ship. |
| | Unit bulk cargo | Large quantities of units that must be handled individually (e.i. logs, lumber, steel products). |
| | Wheeled bulk cargo | Cars, trucks, etc. shipped in large quantities (ship size). |
| General cargo parcels | Loose items | Boxes, bags, drums, machines (small parcels). |
| | Containers | Standard boxes usually 8 feet wide, 8.5 feet high, and in length of 20 feet and 40 feet. Can handle 7 - 15 tons of cargo. |
| | Palletized | Cargo stacked on a pallet that can be handled by fork-lift trucks |
| | Heavy and awkward | Heavy loads up to 2500 tonnes (project cargoes, oilfield equipment, ship sections). |

Figure 8: Physical Cargo Units (Adopted from Stopford)

As shown, each of the physical cargo units only belongs to one parcel size distinction. This means that both parcel size and physical cargo unit can be described by the physical cargo unit of the cargo that is to be shipped. Therefore, this model will define the cargo type by the physical cargo unit that the cargo is shipped by. To reiterate, cargo type alone does not fully describe the cargo.

The cargo type properties relevant to this model are the unit volume and weight capacities, the weight of the empty physical units, and the parcel size. This allows the model to better describe the cargo shipment by defining the total number of artificial physical units of cargo (i.e. containers) needed to carry out the cargo operation. Some cargo types (bulk parcels) do not have containers and therefore no capacity restrictions. Therefore the "Cargo Type" class has the "Unit capacities" and "Unit weight" attributes.

### 6.1.4 Ocean Service Type Class

In addition to the commodity and cargo type of the cargo being shipped, the demand for transport must also be characterized by the service level requirement of the shipper. There are four main aspects that define the transportation service that is demanded of a transportation supplier (Stopford, 60).

1. Price: The cost of the transportation service. Shippers are always concerned with finding ways to minimize freight cost.
2. Speed: High value commodities need to be moved faster because of the inventory costs of cargoes on long journeys
3. Reliability: Shippers may be prepared to pay more for a guaranteed service
4. Security: For high value or fragile cargoes

The services demanded by the modern world sea trade can be differentiated into three main segments or modes: industrial shipping, tramp shipping, and liner shipping. These segments have evolved in response to the service demands of the global maritime trade over the past 50 years. These segments differentiate the service demand level from a transport supplier by characterizing the transportation objectives of the shipper. Each of the services encapsulates a combination of the four main aspects of service level as described above.

- *Industrial Shipping Demand*: The shipper's objective is to minimize the cost of high-volume (bulk cargo parcels) dry and liquid bulk trades. The shipper is typically a vertically integrated company in trades such as oil, chemicals, and ores (Christiansen). Industrial shippers seek reliability through a committed fleet of ships to carry-out the majority of their demanded trade.
- *Tramp Shipping Demand*: The shipper's objective is to fill transport demand that is not covered by their industrial shipping operation (seasonal and market variations). Tramp operations usually carry bulk parcels. These shippers are subject to the market prices for shipping services. There is less reliability in utilizing tramp shipping because of the uncertainty of ship availability. Tramp shipping demand may also be generated by one-time or irregular shipments of a medium to large parcel.
- *Liner Shipping Demand*: The shipper's objective is to ship small parcels of general cargo.

With respect to the freight model in question, the service demand types will serve to directly define which of the available shipping services will carry out the transport operation.

The shipping service demand is in part determined by the cargo and commodity, and not all service demands are compatible with every commodity and cargo type. In general, liner shipping demand is by generated general cargo parcels while industrial and tramp shipping demand is generated by bulk cargo parcels.

### 6.1.5 Ship Type Class

In addition to the service type of the cargo being shipped, the demand for transport must also be characterized by the ship type required to move the cargo. Figure 9 identifies the ship types that make up the commercial fleet. Ship types are distinguished by their physical design and the types of cargoes they can carry. For example, container-ships have hold designed to hold containers, bulk carriers have holds for loos cargos, and tankers have tanker for holding liquids (Stopford, page). Therefore, within the generic framework, it is necessary that ship types are distinguished by the cargoes they can carry.
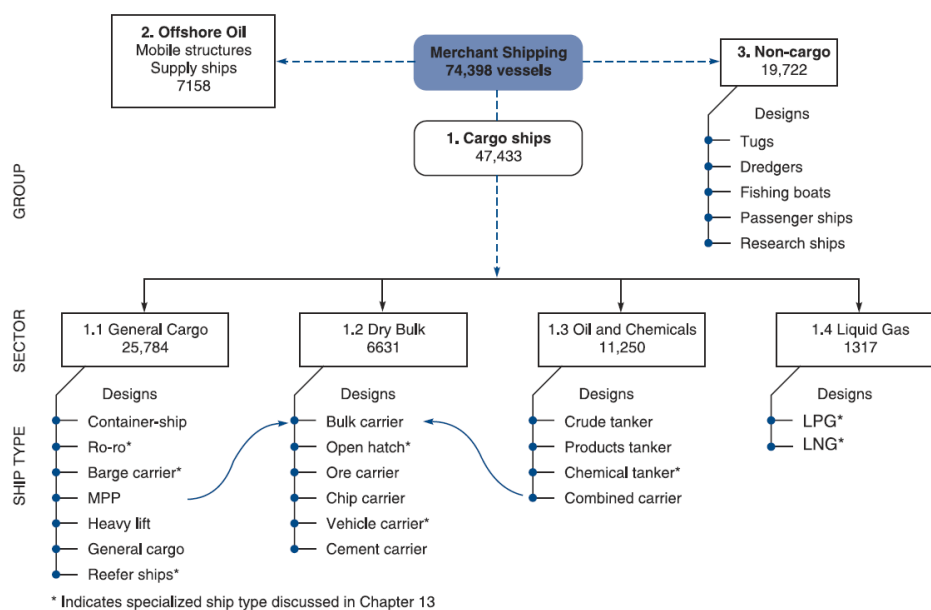
Figure 9: Make-up of the merchant fleet, July 2007 (Stopford, page)

For a given cargo type and commodity, there can be several ship types that can accomplish the transport task. However, specialized bulk shipping operations only have one available ship type as is the case with car carriers or liquefies gas carriers. Containerized cargoes also exclusively demand containerships or ships capable of carrying containers.

### 6.1.6 Inland Mode Class

Similarly to ship type, the demand for transport must be characterized by the inland modes that are required to move the cargoes. There are three primary inland modes that carry freight; truck, train, pipeline, and aircraft. Each of these inland modes is capable of carrying certain cargoes. Therefore within the generic framework, it is necessary that inland modes are distinguished by the cargoes that they can carry.

## 6.2 ORIGIN AND DESTINATION MODELING

All demanded maritime freight movements must be defined by both the origin and the destination of the freight movement. As discussed in the requirements sections, a freight model may be used to analyze a transport operation between a specific origin and destination, between a specific origin and a multitude of destinations, or between a multitude of destinations and a specific origin. Therefore a generic model must support the functionality to define the demand origin and destinations specifically as well as broadly.

### 6.2.1 Origin and Destination Modeling Framework

As with the cargo domain model development, it is useful to generally present the origin and destination domain model before the classes and associations are developed. Figure 10 shows the origin and destination domain model. There are two primary functions of this part of the model:

1. Store the transport activity parameters related to the origin and destination infrastructures.
2. Provide a means of creating all feasible origin and destination solutions starting from any class in the model package.

The major practical functionality provided to the generic mode by this package is the capability to define all origin and destination alternatives for a commodity trade between two regions or countries. This is essential in fulfilling the region-based aggregated analysis functional requirement of the model.

The following will present an example of how the model defines a feasible origin-destination combination. Staring with the "Commodity" class, a commodity object is selected, which generates all feasible "Region" objects. The "Region" object selection and the "Inland Mode" selection then generate all feasible "Production Center" and "Distribution Center" objects. These selections then generate all feasible transport volumes between the

selected PC and DC that are included in the model. Object selection in each of these classes can then be made to fully define the origin and destination.
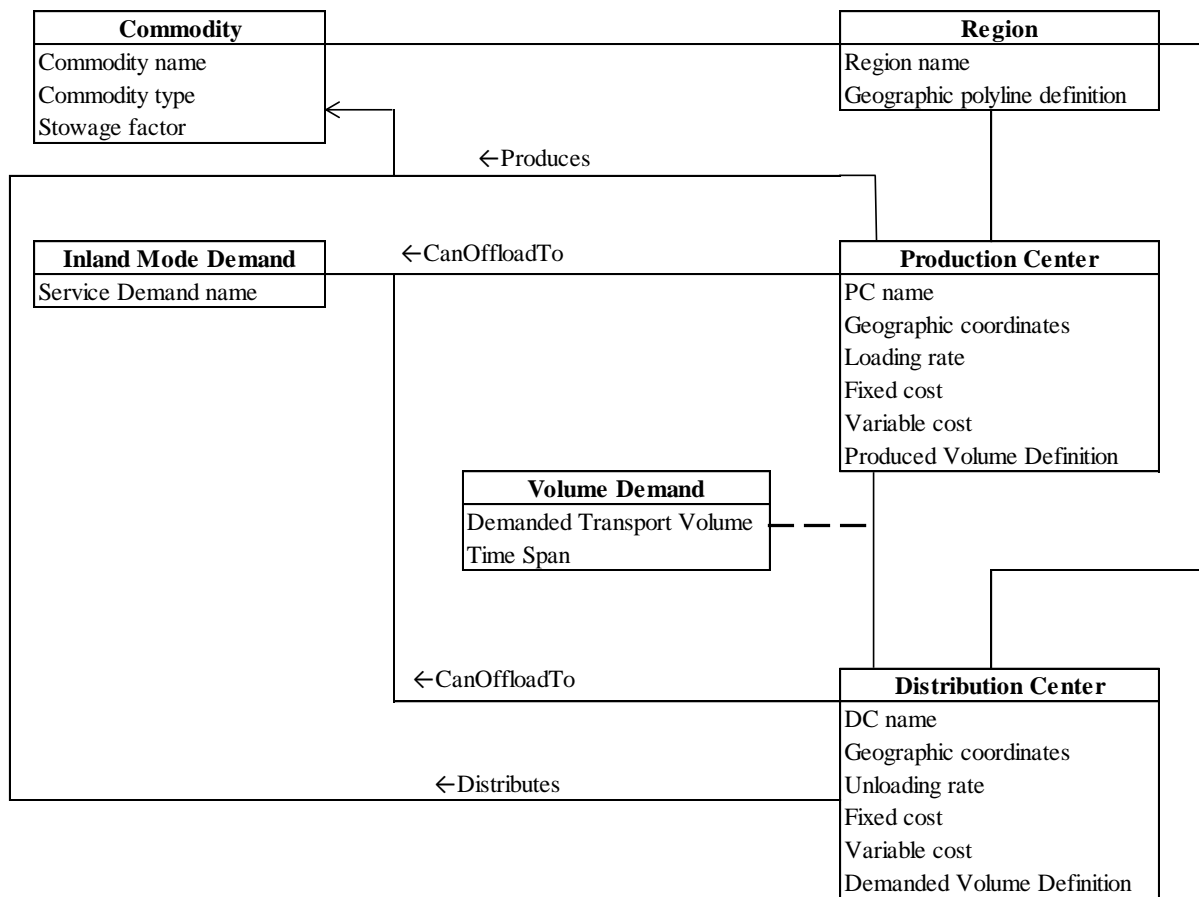


Figure 10: Origin and destination domain model

**6.2.2 Region Class**

To fulfill the requirement of the model to be able to perform aggregate analyses based on the regions and the countries involved in the trade, the definition of the origin and the destination of the trade must begin with the region selection. Before this can be done, global regions must be defined. Region definitions must accommodate the type of trade to be analyzed as well as the available statistics. Historically, region definitions have been a source of difficulty for trade analysts because of their dynamic and political nature (Stopford).

The demand for freight transportation is largely generated by multinational companies that source raw materials where they are the cheapest, manufacture products in low cost nations, and distribute goods where they are demanded (Stopford). This has resulted in intercontinental and interregional trade patterns specific to certain commodities. Because of this, it is interesting to study the aggregated movement of a commodity between specifically

defined regions of the world. These regions must be defined appropriately for a given commodity in order to accurately model an aggregated commodity movement. For example, the Far East is both a major importer of LNG (Japan) and producer of LNG (Malaysia, Indonesia). Therefore, when looking at the major trade movements of LNG to the Far East, it may be advantageous to include the Malaysian and Indonesian exporters in the same region as Australia, as it is also a major LNG exporter.

The "Region" class must provide the model with region definitions that allow the model to assign infrastructures to regions based on their geographic coordinates.

As explained, the region definitions must also be flexible as to allow commodity-based region distinctions. These two requirements make it useful to model region definitions with closed polylines that surround each region and the infrastructures within it. Therefore, the "Region" class must store data to name the regions and define them with closed polylines on the geographic coordinate system.

### 6.2.3 Production Center (PC) Distribution Center (DC) Classes

The origins and destinations in this model will be referred to as production centers (PCs) and distribution centers (DCs). This designation encapsulates the scope of the model by making it clear that it only covers the transportation of the cargo between two locations and nothing beyond that. For example, in LNG shipping, the boundaries of any analysis done with this mode are the liquefaction plant loading terminal (PC) and the regasification plant offloading terminal (DC). It would not include any processes regarding the liquefaction or regasification of LNG.

There are several properties of PCs and DCs that are important in both integrating the infrastructures into the maritime transportation network and analyzing the performance of the transportation system. The PC or DC commodity and hinterland connection are needed to make network connections with other necessary transport infrastructures (ports). The PC and DC location, region, and country are necessary in aggregate analyses and for transport distance calculations. Various transport activity parameters are also necessary to measure the performance of the entire transport operations (unloading/loading rates, etc…).

When modeling transportation infrastructure within a generic model there are three major distinguishing characteristics: the commodity serviced at the infrastructure, the type of infrastructure (port, rail terminal, truck terminal, etc.), and the available hinterland network

connections (truck, train, pipeline, etc.). In addition, transportation infrastructures have names and varying transport activity parameters (unloading/loading rates, storage capacities, etc.).

### 6.2.4 Volume Demand Association Class

The "Volume Demand" association class provides the model with the capability to store demanded transport volumes and the time span that these shipments are to be completed in. This information represents the physical cargo movement between an origin and a destination. Because different types of planning problems are done over different horizons, the time span attribute of a cargo movement is necessary.

## 7. SUPPLY MODELING MODULE

The purpose of this module is to define the supply of maritime transportation that fulfills the freight transportation demand as defined in the maritime transport demand module. Within this model, maritime freight transport refers to the intermodal transportation of freight from and inland origin to an inland destination that involves an ocean shipping service. This distinction is made to accommodate the growing level of integration between ocean shipping services and inland freight transport systems (Panayides, 2006). The supply of international maritime freight transport is composed of two main segments, the shipping services which employ vehicles and are flexible in their geographic position, and the supporting infrastructure, which is spatially fixed. The following section will further define each of these aspects of maritime transport supply and also develop a domain model package that can effectively represent the demand for freight transport within a generic sea transport model. The development will include discussion on how certain characteristics this package fulfill the requirement of the generic model as a whole.

### 7.1 INFRASTRUCTURE AND ROUTE MODELING

A model of maritime transport supply must include a sufficient description of the routing of the cargo between the origin and destination. As previously discussed, a maritime freight movement is composed of an inland leg from the origin to a port, an ocean leg from a port to a port, and a second inland leg from the destination port to the cargo movement destination. The origin (PC) and destination (DC) of the cargo movement is defined by the demand for maritime freight transportation. Therefore, the infrastructure and routing descriptions need to define the supply of transport is composed of the ports and the routing options (depending on

transport mode) available between the infrastructures involved. The following sections will further discuss these elements of sea transport supply and develop infrastructure and route modeling framework using the generic modeling blocks as previously presented.

### 7.1.1 Domain Model

To understand the development of the infrastructure and routing blocks, it is useful to present the framework in which they will act. Figure 11 shows the infrastructure and routing conceptual modeling framework. There are two main goals of the infrastructure and routing modeling framework and the blocks within it.

1. Store the data needed to describe both the infrastructures (transport activity parameters) and routes (distances) involved in a cargo movement.
2. Provide a means of listing the feasible routes and infrastructures involved in a demanded cargo movement based on the origin and destination, the transport modes, and the commodity.

The major functionality provided to the model by this part of the framework is the capability to connect at PC and at DC through an import port and an export port as well as define the routing between the ports.
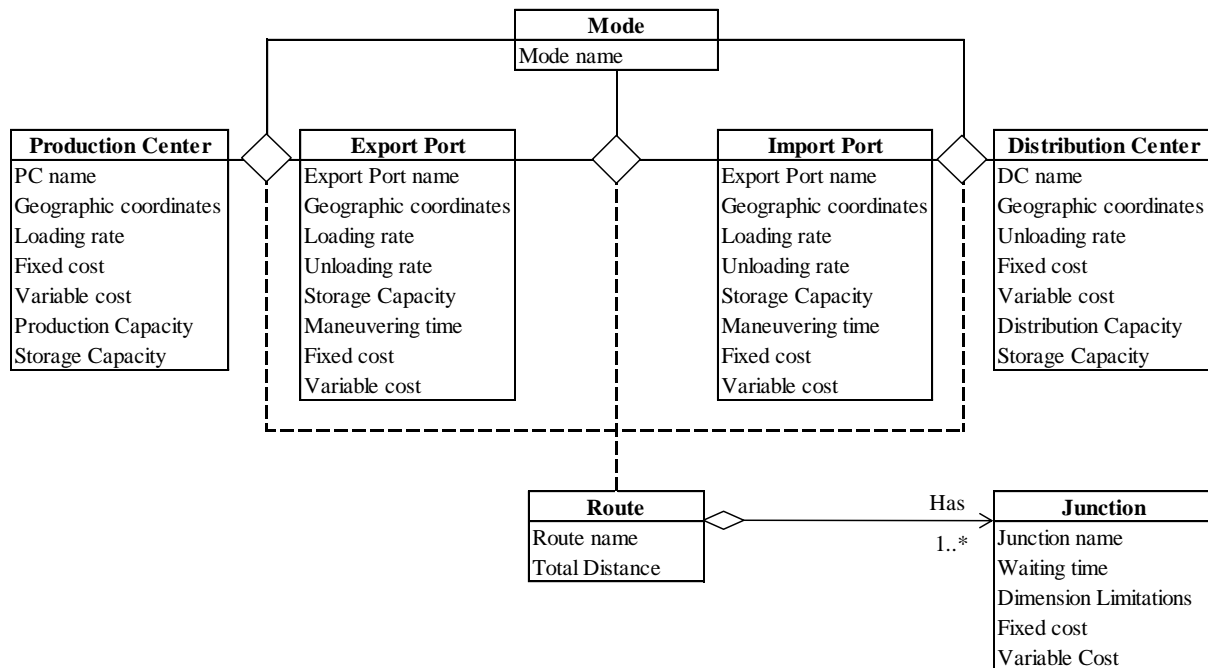


Figure 11: Intermodal route modeling package

### 7.1.2 ExportPort and ImportPort Classes

Ports are crucial facilities where maritime and land vehicles converge. Maritime freight movements require port terminals to load and discharge cargo from ocean going vessels to other modes of transportation to carry out the hinterland leg. Port terminals have several distinguishing characteristics that are relevant to this model. Port terminals are unique in that they are not all capable of handling all cargo types and commodities. They also have limited connections to other modes of transportation for the hinterland leg of the transport operation. There are also many operation limitations for terminals such as vessel draft limitations.

Therefore, to integrate a port terminal into the transportation network model, it must be defined by its type (export or import), the commodities it services, and the available inland transport connections. For the purposed of measuring transport performance and aggregating the analyses, port terminals must also have location definition and transport activity parameters.

Freight transportation vehicles move cargo between an origin infrastructure and a destination infrastructure. In accomplishing this, they may take a variety of routes and visit one or several junctions. Junctions are geographic locations where many routes converge and though which vehicles pass when travelling from one main area into another. For example, the ship junction point for all routes from Atlantic to the west coast of the US is the Panama Canal.

### 7.1.3 Route Association Class

The physical movement of a vehicle between junctions or between transport infrastructures or between a junction and a transport infrastructure is referred to as a leg. A feasible combination of a leg and two end points (junctions or transport infrastructures) is referred to in this model as a route segment.

In this model, a feasible transport solution contains route segments that connect a production center to an origin port, routes that connect the origin port to the destination port, and route segments that connect the destination port to the distribution center. In order to define the routes, both the transport infrastructures and the connections between them must be established.

**7.2 MARITIME TRANSPORT SERVICES MODELING**

A model of maritime transport supply must include a sufficient description of the services that carry out freight movement tasks. Ocean services are defined by the vessels that they are made up of, the ports of call of the service, and the operational profile of the vessels on the legs of the service.

**7.2.1 Domain Model**

Figure 12 shows the domain model for the ocean services modeling package. There are two main goals of the services modeling framework and the classes within it.

1. Store the data needed to describe both the services and the ships in the services.
2. Provide a means of listing the feasible service supply alternatives to fulfill a transport demand.

The major functionality provided to the model by this part of the framework is the capability to match the demands with a feasible supply solution.
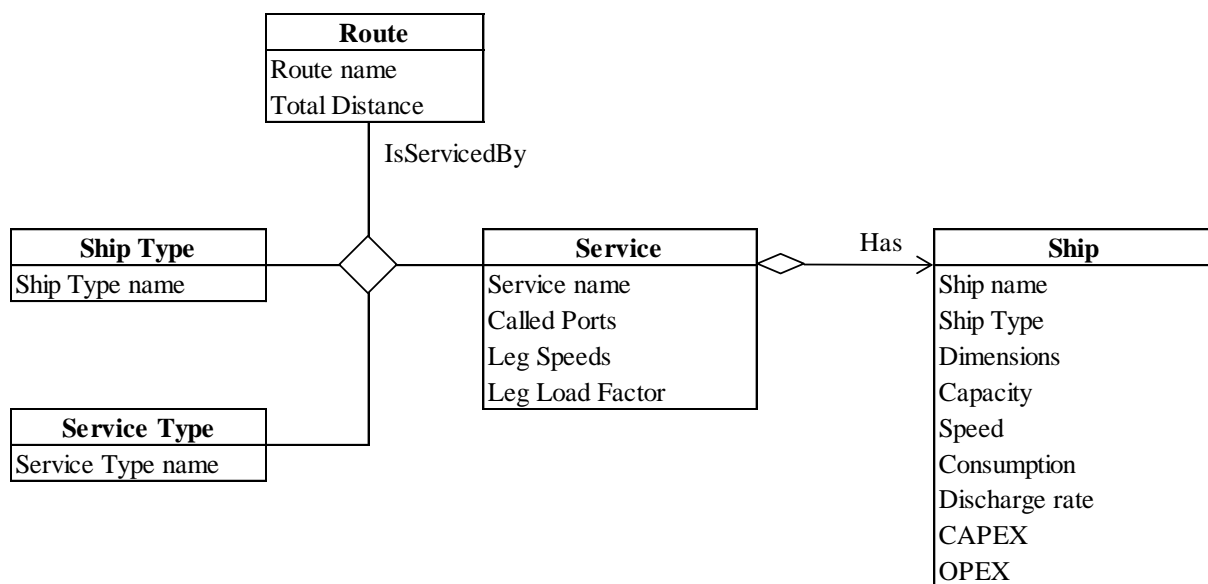


Figure 12: Services modeling package

**7.2.2 Ocean Service class**

A transportation service is a service provided to transport freight from a departure point to a destination point (European). Transportation services have evolved into three major modes of operation to accommodate the transportation demand profile of modern global sea trade. The three transportation service types are: industrial shipping, tramp shipping, and liner

shipping. These service types are differentiated by the objectives of the carrier in a transport operation.

- *Industrial Shipping Service*: The objective of an industrial carrier is to provide a reliable transport service to a committed transport operation at minimum cost. Industrial carriers are often vertically integrated into the company owns the cargo. Industrial carriers are usually involved in bulk trades.
- *Tramp Shipping Service:* The objective of a tramp carrier is to follow available cargoes that demand tramp shipping in an effort to maximize profit. Tramp shipping may be used to supplement the under-capacity of an industrial shipping operation. Tramp shipping services are usually involved in bulk trades.
- *Liner Shipping Service:* A liner shipping service operates according to a published schedule, calling several ports on a given line. Liner shipping services typically carries general cargo on container ships or general cargo ships.

The major goal of the transportation model is to estimate the energy consumption and emissions of a transport operation. This means that the transportation service modeling must describe the how the different operational characteristics of each type of shipping service effects the emissions and energy consumption of a given transport operation. This can be accomplished by estimating the energy consumption of the vehicles involved in the transport operation and allocating a share of the total energy consumption of the vehicles to the movement of the freight of interest.

## 8. COST ANALYSIS MODULE

The output of the previous module was to generate feasible transport alternatives based on the user input and store the transport activity parameters associated with the alternatives. The function of this module is to calculate the cost associated with each of the transport solution alternatives. The cost analysis module consists of two main segments: ocean service cost calculation, and specific freight movement cost calculation.

Determining the cost of a specific freight movement can begin by considering the cost associated with the shipping service carrying out the freight movement. Once the cost associated with the shipping service is known, the cost of a specific freight movement performed by the service can be estimated by allocating some the total service cost to the freight movement in question. Although there are multiple ways to estimate this allocation, it

is common to use the ratio of the transport activity[1]of the cargo operation of interest to the transport activity of the service carrying out the transport operation (European).

This methodology is convenient because it provides a consistent procedure that works with all ocean shipping service types. For example, in industrial shipping, the specific freight movement in question is often equal to the entire capacity of the service. In this instance, the total shipping service cost would be allocated to the specific freight movement. In liner shipping, the specific freight movement in question is often only a small percentage of the capacity of the service. In this instance, only an equally small percentage of the service cost is allocated to the freight movement in question.

Furthermore, this methodology is valid across multiple modes of transport, and also provides a method for using service data collected over any time frame to be used to describe any given cargo operation, with only certain limitation. This is because a performance measure like cost or fuel consumption of a vehicle per transport activity unit can be collected over any time frame and is generally usable to describe a single transport operation.

## 8.1 THE COST OF RUNNING SHIPS

There is no internationally accepted standard for cost classification or terminology for running ships. This study will use an approach adopted by Stopford. The costs of running a ship can be classified into five categories:

- **Operating Costs:** Commonly abbreviated as OPEX; the expenses involved in the day-to-day running of the ship. This includes the costs such as crew, provisions, maintenance, insurance, and management overhead. These costs are incurred no matter the trade the ship is engaged in.
- **Periodic Maintenance Costs:** Costs incurred when the ship is dry-docked for major repairs, usually at 5 year intervals in time for its classification survey. These costs are not treated as operational costs because they can represent considerable expenditure, especially in older ships.
- **Voyage Costs:** Variable costs associated with a specific voyage which includes fuel, port charges, and restricted passage or canal dues.
- **Capital Costs:** The cost of financing the capital cost of building a ship. This can be represented in two different ways:

---

[1] Transport activity refers to a cargo volume multiplied by the distance the cargo volume is transported.

1. The cost of the capital (interest on a loan or dividends to equity) and the depreciation of the ship (yearly cost of the vessel devaluation).
2. Loan repayments which include the capital and interest payments to a loan and/or dividends to equity.

The second option considers cash flow directly while the first option uses a balance sheet approach. Each method should yield a similar number for cost as depreciation and loan repayment are often similar figures.

- **Cargo-handling costs:** The cost of loading, stowing, and discharging cargo.

Each of these categories can be further broken down into cost items. It is necessary to identify cost items in this study because some cost items interact among different actors within a maritime freight system. Figure 13 shows the breakdown of the cost categories into cost items.

| COST CATAGORIES | COST ITEMS |
|---|---|
| **1. OPERATING COSTS (OPEX)** | Manning Costs |
| | Stores and Lubricants |
| | Repairs and Maintenance |
| | Insurance |
| | General Costs |
| **2. PERIODIC MAINTENANCE** | n.a. |
| **3. VOYAGE COSTS (VOYEX)** | Fuel Cost |
| | Port Costs |
| | Canal Tariffs |
| **4. CARGO-HANDLING COSTS** | n.a. |
| **5. CAPITAL COSTS (CAPEX)** | Interest/dividend |
| | Debt repayment/depreciation |

Figure 13: Cost items involved with running ships (adopted from Stopford)

## 8.2 OCEAN SERVICE COST CALCULATION

As discussed, each service contained in the model is defined by ports of call and the legs between the ports of call. Therefore, the cost of an ocean service can be estimated by calculating the cost of operating all vessels in the services between all of the ports that each vessel in the service calls. In this model, the combination of two ports and a leg between

them is referred to as a route segment while a route is the combination of route segments that a service completes (European).

In order to make the cost calculations representative of the entire operation of the fleet, a service route must be composed of a full round-trip, including the ballast voyages (European). In general, industrial shipping routes are composed of two segments; a laden voyage and a ballast voyage. Liner shipping is composed of many route segments because they often call many ports. Again, a liner shipping service must be defined by a full round-trip of route segments. Tramp shipping is harder to capture with this methodology because this service has no set route, and follows cargoes. One method is to assign a tramp vessel with an average starting point and then represent the service with three route segments, the first being a ballast voyage from the starting point to the loading port, the second being the laden voyage from the loading port to the discharge port, and the third being the ballast voyage from the discharging port back to the starting point.

This methodology presents obvious issues, because the selection of the starting point cannot be well defined. Perhaps a better way to model the cost of tramp services is to use directly measured data from representative tramp services estimate transport activity costs.

**8.2.1 Route Segment Cost Calculation**

The route segment cost calculation developed and used in this module can be found in Appendix A. The input parameters to the route segment cost calculation are taken directly from the domain model classes based on the object selections that define a transport solution alternative. The outputs of this calculation include the total route segment duration, the fuel consumption, the cargo movement, the transport activity, and costs break-down (OPEX, VOYEX, and CAPEX).

**8.2.2 Ocean Service Cost Calculation**

For a given service, the route segment cost calculation must be performed for each ship – route segment combination in the service definition. This gives the ocean service cost for each ship in the fleet completing the full round-trip route. In order for the cost calculation to support all planning problem types, the cost of an ocean service is also calculated for specified time duration (often annual).

## 8.3 SPECIFIC TRANSPORT OPERATION COST CALCULATION

As mentioned, the cost of a specific transport operation is estimated with this module by allocating a certain amount of the cost of the service operation to the specific movement based on transport activity. This makes this calculation rather simple in comparison to the service cost calculation. This is beneficial, from a software implementation point of view because a database of pre-calculated service costs can be used to rapidly access the cost of transport solution alternatives. This functionality could be essential in the implementation of a sophisticated optimization tool with the generic model.

## 9. EXCEL VBA PROGRAM DEVELOPMENT

The domain model and cost analysis was implemented into an MS Excel VBA application. The following sections will explain the functional objectives of the program, a general description of how the program operates, how the domain representation of the model was implemented into the program, how the data within the program is managed, and how the user interacts with the program.

## 9.1 FUNCTIONAL OBJECTIVES OF THE PROGRAM

The primary function of the program is to provide the user with an effective and rapid method of generating and assessing feasible transport solutions for a potentially large number of transport demands all based on the developed generic model. The secondary objective of the program is to implement a basic tool for matching the supply to the demand based on a basic objective.

## 9.2 PROGRAM STRUCTURE

Figure 14 shows the structure of the program. The database is made up of a collection of MS Excel worksheets that cater to the generic model framework. This data is managed either directly by the user or by sub routines which populate certain worksheets using data from other parts of the database. The generic modeling framework is implemented as a collection of sub-routines that populate the user forms based on the data contained in the database. These sub-routines also generate lists of feasible transport demands and supply based on the user inputs. The service supply cost calculation module calculates the costs associated with all service supply solutions as generated by the generic model framework.
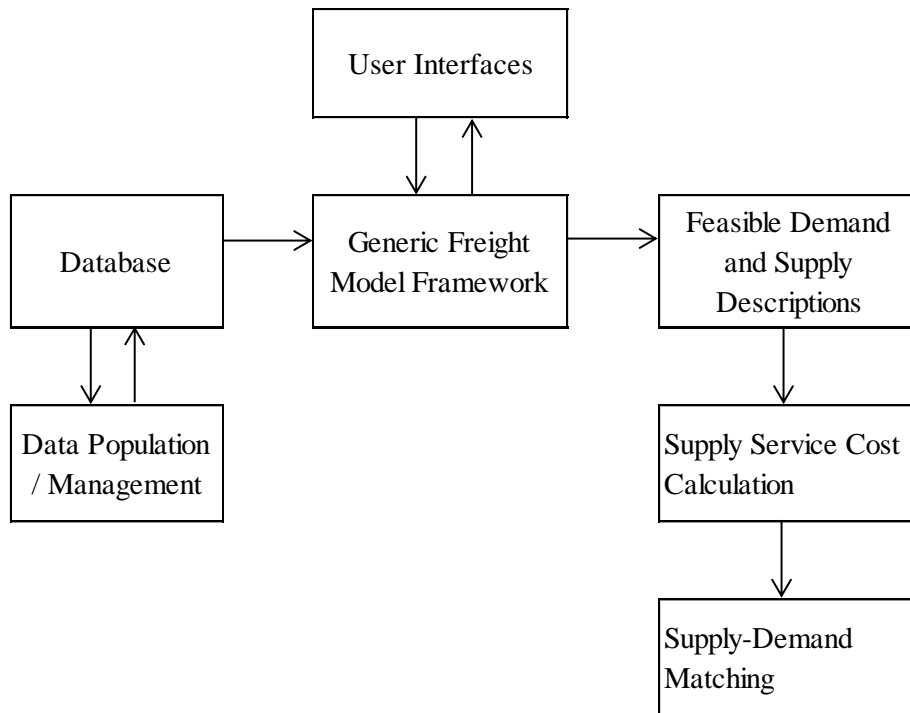
Figure 14: Program Structure

## 9.3 DATABASE STRUCTURE

The structure of the database was developed to resemble the classes and associations in the domain model. This was done to increase the transparency of the connection between the domain model and its implementation into the program.

In general, the classes and association in the model are composed of collections of worksheets that hold the necessary data to model the domain objects and the associations between them. The following sections will shows how this data is stored by explaining the worksheet naming schemes and the structure of the data as it is stored within the worksheets.

### 9.3.1 Class Implementation

Each class in the model is implemented into the program as a collection of one or more worksheets that hold all objects, and their attribute values, that can be created by the class. As a means of making the data structure less cumbersome and easier to manage, it is often the case that multiple worksheets are used to store the data for objects within the same class. This is also done as a means of making it faster for the sub-routines in the program to search for class objects and their attributes.

For example, the worksheet named "PC_LNG_DIR", as shown in Figure 15, stores the PC objects (specific infrastructures) only for PCs that produce LNG and have a direct inland connection (DIR) to an export port. This means that there must be one PC worksheet in the database for each commodity and inland mode to be included in the analysis.

As illustrated in the previous example, the name of the worksheet identifies both the class the worksheet belongs to and the second-party objects that are linked, through associations, to the objects in the class the worksheet is storing data for.

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | PC name | Country name | Latitude | Longitude | Dec. Latitude | Dec. Longitude | Region |
| 2 | Sabine Pass LNG Terminal | Louisiana, United States | 29°52'00"N | 93°56'00"W | 29.867 | -93.933 | USG and Caribbean |

Figure 15: "PC_LNG_DIR" PC class worksheet

Some classes in the model are only represented in the model with one worksheet, as is the case with the "Commodity" class. The worksheet, named "Commodity" that stores all of the data for the "Commodity" class is shown in Figure 16.

| | A | B | C |
|---|---|---|---|
| 1 | Commodity name | Commodity Type | Stowage Factor [m$^3$/MT] |
| 2 | LNG | Energy | 2.20 |
| 3 | Heavy Crude Oil | Energy | 0.95 |
| 4 | Light Crude Oil | Energy | 1.07 |
| 5 | Iron Ore | Metals | 0.40 |
| 6 | Grain | Argiculture | 1.30 |
| 7 | Coal | Energy | 1.40 |

Figure 16: "Commodity" worksheet with sample data

For all class worksheets, the first row of the worksheet holds the names of the attributes associated with the class, including the object names (Commodity names in the case of the "Commodity" class). The commodity objects and their attribute values are then listed below. This system is followed for all class representations in the program.

### 9.3.2 Attribute Implementation

Each association in the model is implemented into the program as a collection of worksheets that stores the links between objects in the classes that the association is relating. Each worksheet is capable of linking the objects in two classes.

For higher-order associations, multiple worksheets are needed. The name of the association worksheet identifies the classes that are involved in the association as well as the direction of the association and which object is held constant. For example, the association between the classes, "Cargo Type", "Service Type", and "Commodity" is partly implemented in the program with the worksheet "CargoTypeToServiceType_LNG" as shown in Figure 17. The worksheet name implies that the worksheet links service types to cargo types for the fixed commodity object, LNG. To fully represent this association a separate worksheet is needed for every commodity included in the model.

Figure 17 also shows the layout of the association sheet. The first row shows the classes that are being related in the association. The first column lists the cargo type object names while the compatible service types for each cargo type are listed to the right in the same row as the cargo type of interest. This system is followed for all associations included in the program.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | **CargoType name** | **ServiceType name** | | |
| 2 | All CargoTypes | Industrial Shipping | Tramp Shipping | Liner Shipping |
| 3 | Liquid bulk cargo | Industrial Shipping | Tramp Shipping | |
| 4 | 40' LNG Container | Liner Shipping | | |
| 5 | 20' LNG Container | Liner Shipping | | |

Figure 17: "CargoTypeToServiceType_LNG" association worksheet

### 9.3.3 Analysis Storage

Several worksheets are needed to stores the feasible solution alternatives, the cost calculation, and the results of the cost calculation. A list of these worksheets and a short description of the function of each is presented in the following table.

### 9.3 DATA MANAGEMENT

The worksheets presented in the previous section need to be populated with various types of data in order for a transportation analysis to be performed. While the majority of the data

held in the worksheets requires manual upload, some of the association worksheets and attributes values are derived and populated by VBA code that uses data already in the model. This is indicated in the worksheet by the color of the cells: grey cells indicate that data must be manually entered into the program by the user while the white cells indicate that data is populated by coding and data from other parts of the model.

It should be noted that the grey cells, or the cells that require manual inputs, can also be manipulated or varied with, for example, an external optimization code. As a specific example, the speed that a ship operates on a given leg of a service is a user input value, but can become a variable in an optimization code. This is not possible with grey-cells as they are populated with fixed data management code. The following sections will explain how and which data is populated with built-in coding.

### 9.3.1 Region Assignment to Infrastructures

One of the function requirements of both the domain model and the program is the support for variable definition of regions using geographic coordinate polylines. The reasoning and importance of this functionality is explained in section 6.2.2. This functionality demands the ability for the program to assign regions to the various infrastructures includes in the model based on the user region definition. This is accomplished by the coding presented in Appendix B. There are five main steps to this code module:

1. Collect the names of the input data and output data worksheets. This is done for all worksheets in the model that hold infrastructure data.
2. Convert the infrastructure latitude and longitude user inputs into decimal values and display them back in the infrastructure list worksheet.
3. Use a winding number algorithm[2] to determine which region each of the infrastructures in the input list belongs to (Miranda).
4. Output the region assignments back in the infrastructure list worksheet.
5. Populate the association worksheets that rely on region assignment.

The results running the above steps 1-4 in the code populate the white cells in Figure 18. Step 5 populates worksheets for the infrastructure of interest. This code is repeated for all infrastructures for which data exists in the model. This creates all worksheets that are demanded by the classes that rely on region assignment attributes.

---

[2] A commonly used algorithm for determining is a point lies within a polygon (Miranda).

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 1 | PC name | Country name | Latitude | Longitude | Dec. Latitude | Dec. Longitude | Region |
| 2 | Sabine Pass LNG Terminal | Louisiana, United States | 29°52'00"N | 93°56'00"W | 29.867 | -93.933 | USG and Caribbean |
| 3 | Qatargas 1 LNG Plant | Qatar | 24°53'30"N | 51°34'00"E | 24.892 | 51.567 | Middle East |

Figure 18: Region assignment results example ("InfraList_LNG_PC_DIR" worksheet)

### 9.3.2 Route Generation

A functional requirement of the program is the ability to generate route descriptions between all major shipping ports. The route descriptions demanded by this model are the total distances between ports and the major way points or junctions between ports. As explained earlier, this is essential in generating transport solution alternatives and in measuring the costs and capacities of transport services.

The data used for the route generation code is from a United States government National Geospatial-Intelligence Agency publication entitles "PUB. 151 DISTANCES BETWEEN PORTS" (National). This data uses major junction points as a method of reducing the number of distances that need to be included give the distances for every possible combination of ports. Some of the junctions included in the data include the Panama Canal, the Suez Canal, and the Straits of Gibraltar. This data suits the model well as it allows routes to be described not only by distance, but also by the junctions involved.

This data was originally found in PDF form and was uploaded to an excel sheet. A pre-processing sub-routing was created to sort the data and put it in a more useable form. A second route generation sub-routing is used to generate the distances and junctions given an input of origin and destination ports. The route generation sub-routing is run in the data-management stage of program usage. This sub-routine can be found in Appendix C. The purpose of this sub-routine is to populate a worksheet with the route data needed for only the infrastructures included in a specific instance of the model. The reasoning behind this is that it avoids running the demanding route-generation sub-routine for each feasible supply solution generated by the model.

### 9.4 PROGRAM UTILIZATION AND INTERFACES

This section will present how the program is used to generate and assess feasible transport solutions. This will be accomplished with a program flow chart and by explaining the user interfaces with sample data shown. Figure 19 shows the flow chart of the program and the

locations, both within the program and in the appendices, of the code associated with each program step. The detailed use of the program will be presented in the case study.

| Main Steps | Sub-Steps | Sub-routines | Program Location | Report Location |
|---|---|---|---|---|
| Manual Data Entry | Demand worksheet inputs<br>Supply worksheet inputs | | | |
| Programmed Data Management | Call data management sub-routines<br>Region Assignment<br>Route Generation | UpdateData<br>Region Assignment<br>Route Generation | Module1<br>Module7<br>Module4<br>Module5 | Appendix B<br>Appendix C<br>Appendix C |
| Program Start and User Form Input | Start Program: Upload Data and Initiate User Forms<br><br>Transport Demand Description<br><br>Transport Supply Description | Program Start<br>Association Data Upload<br>Class Data Upload<br>Demand User Form<br>Supply User Form | Module1<br>Module2<br>Module10<br>UserForm-TransportDemand1<br>UserForm-TransportSupply1 | |
| Feasible Solution Generation | Demand Solution Descriptions<br>Supply Solutions Descriptions | Feasible Solutions | Module6 | |
| Cost Calculation | Calculation Input<br>Service cost calculation<br>Transport operation cost calculation | Feasible Service Data Upload<br>Service Cost Calculation | Module11<br>Module12<br>Module9 | |
| Supply-Demand Matching | Objective Function Input | SupplyMatching | | |
| Results | Vessel Traffic Flows<br>Required Freight Rate (RFR)<br>Profit | | | |

Figure 19: Program flow chart

## 9.4.1 Transportation Demand Alternatives Generation

Figure 20 shows the user interface where the user defines the variables needed to describe the demand that is to be included in the analysis. When the "Proceed to Transport Supply" button is clicked, a worksheet is populated with all demands included in the model that fit the selections in the user form.

Figure 20: Transport demand user form

The following bullet points outline the process of defining the demand by explaining each list box and how they are populated. The code behind the user forms and the population of the list boxes can be found in Appendix G.

- **Commodity:** Allows the user to select the name of the commodity. This list box is populated with the "Commodity" class object names upon the user form initiation. A specific commodity must be selected before proceeding. If the user wishes to generate feasible demands for more than one commodity, multiple runs of the program are necessary.

- **Cargo Type:** Allows the user to select the cargo type. This list box is populated when the drop-down button is clicked with all possible cargo types for the selected commodity. If the user wishes to generate all feasible demands that include all cargo types, the "All Cargo Types" selection can be made.

- **Service Type:** Allows the user to select a demanded service type. This list box is populated when the drop-down button is clicked with all possible services from the

selected commodity and cargo type combination. If the user wishes to generate all feasible demands that include all feasible service types, the "All Service Types" selection can be made.

- **Ship Type:** Allows the user to select a demanded ship type. This list box is populated when the drop-down button is clicked with all possible ship types from the selected commodity and cargo type combination. If the user wishes to generate all feasible demands that include all feasible ship types, the "All Ship Types" selection can be made.

- **Inland Modes:** Allows the user to selection an inland more type. This list box is populates when the drop-down button is clicked with all possible inland mode types based on the commodity and the cargo type.

- **RegionA/B**: Allows the user to select the region of origin of the trade (where the production centers are located). This list box is populated with all regions that hold production centers for the selected commodity and inland mode.

- **CountryA/B**: Select the country of origin of the trade (country where the PC is located). This list box is populated with all countries within the selected RegionA that hold PCs for the selected commodity and inland mode.

- **Production Center / Distribution Center**: Select the PC involved in the trade. This list box is populated with all PCs within the selected Region and Country that also fit the other previous selections.

## 9.4.2 Transportation Supply Alternatives Generation

With the demand defined, the user can then further define the supply by making port and service selections. The available selections are populated based on the demand definition. Figure 21 shows the user interface that is used to define the supply. When the "Populate List of All Transport Alternatives and Proceed" button is clicked, a worksheet of all feasible transport solutions that can fulfill the demand in the demand matrix is populated.

Figure 21: Transport supply user form

- **Export Port /Import Port name**: Allows the user to select the name of the export ports available for the transport operation. This list box is populated with the "Port" class object names that are feasible with the demand description. If the user wished to include all feasible ports in the analysis, the "All Ports" selection can be made.

- **Service name**: Allows the users to select the name of the services available for the transport operation. This list box is populated with the "Ocean Service" class object names that are feasible with the demand description and the port selections. If the user wishes to include all feasible ports in the analysis, the "All Services" selection can be made.

## 10. APPLICATION IN AN LNG SHIPPING CASE STUDY

The intention of this case study is to demonstrate both the capabilities of the generic model and the use of the developed MD Excel VBA tool.

### 10.1 CASE STUDY PROBLEM INTRODUCTION

The United States is set to start exporting LNG from the Gulf Coast starting in 2015. The Cheniere Energy import terminal in Sabine, LA has been undergoing a conversion to give it liquefaction capability, and it is planned to export 18 mtpa [metric tons per annum] once it is fully operable in 2015. It is likely that this LNG will be contracted to mainly the Asia-Pacific market (Henderson).

Currently, only 10% of the world LNG fleet is capable of transiting the Panama Canal because of dimensional limitations. This has been a consequence of both the lack of significant LNG trade between the Atlantic and Pacific basins and the overwhelming benefits gained by shipping LNG around Cape Horn, South America, though economies of scale. However, The Panama Canal expansion is set for completion in 2015, opening up the passage to 87% of the world LNG fleet (Henderson). For vessels travelling from the US Gulf to the Asia-Pacific region, the Panama Canal saved about 2600 nautical miles compared to the shortest alternative route (Henderson).

The appearance of an LNG transport demand from the US Gulf to the Asia-Pacific region and the completion of the Panama Canal expansion project mean that the Panama Canal could see a strong emergence of LNG vessel traffic. However, this is dependent on how much of this traffic transits the competing route (Cape Horn, South America).

Although the Panama Canal expansion will allow large LNG vessels to pass (up to 160.000 cubic meters), the largest LNG vessels today (266.000 cubic meters) will still be incapable of transiting. Because of this, there are potential economies of scale benefits associated with the longer Cape Horn route. In addition to this benefit, the potentially high tariffs imposed by the Panama Canal on LNG vessels may make longer transits around Cape Horn more economically viable.

Given the above scenrio description and the trade-offs involved, it is interesting to create a model to predict the flow of LNG vessel traffic through the Panama Canal and study the effects of fuel cost, the vessels available to move the LNG, and the tariff imposed by the Panama Canal.

## 10.2 CASE STUDY DESCRIPTION

The Panama Canal is interested in maximizing its revenue from the passage of LNG vessels after its expansion is complete. Effectively, the Panama Canal competes with the alternative for LNG exports from the Gulf of Mexico, which is the shipment around Cape Horn to the Asia-Pacific Region. As described in the problem introduction, there are potential economic benefits and drawbacks associated with each route when comparing the alternatives

 The Panama Canal tariff represents a potentially significant voyage expense for LNG shipments to the Asia-Pacific Region, and has the potential to make Post-Newpanamax[3]

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[3] This refers to vessels that are incapable of transiting the expanded Panama Canal.

shipments around the Cape Horn a more attractive option to fulfill the LNG shipment demand in a long-term LNG contract. Therefore, there exists a maximum tariff the Panama Canal should impose on LNG vessels if it wishes to not have LNG shipments from the Gulf to the Asia-Pacific region diverted around Cape Horn. The specific objective of the case study is to determine the Panama Canal tariff that yields the maximum revenue for the Panama Canal. The case study will assess the effects of fuel cost and the vessels carrying out the transport.

### 10.2.1 Scope

This case study will look specifically at the demand for LNG transport created from the production of LNG at the Sabine Pass Terminal, as it will commence in 2015, and its shipment to the Asia-Pacific Region. The first major assumption is that all of this transport activity will be carried out with industrial-type shipping. That is to say that the vessels involved in the transport will seek to minimize their cost while fulfilling a given, transport demand. This is irrespective of if the vessels are owned by the LNG buyer or seller or if they are hired on a long-term contract to fulfill the demand. There are two important implications of this assumption: the LNG cargoes cannot be diverted to other destinations that will yield a higher return for the LNG seller, and the vessels involved are dedicated to the trade and cannot follow other trades with higher freight rates.

### 10.2.2 Methodology

The presented problem was evaluated by considering the current fleet of LNG vessels that will be incapable of transiting the Panama Canal. The operation of the vessels in this fleet to carry out the transport represents the core competition of the Panama Canal. By approaching the problem with this methodology the economies of scale benefit of the Cap Horn route is captured. However, one assumption made by this approach is it does not capture the possibility of ships capable of transiting the Panama Canal diverting around Cape Horn to avoid the tariffs. This assumption is made with confidence because it is likely that the tariff will never be high enough to induce this situation.

### 10.3 CASE STUDY MODELING WITH THE VBA TOOL

The following sections will further define the parameters and variables involved in the case study while showing how these definitions are input and modeled with the VBA tool developed in this thesis.

### 10.3.1 Demand Modeling for the Case Study

Before the user forms are used to describe the demand, the program must have the data relevant to the case study uploaded the various worksheets. In its delivered form, the VBA tools hold all sufficient generic data to describe the commodity, cargo type, service, and ship types for most transport demands. However, it is necessary to upload the data related to the production centers and distribution centers to be included in the analysis, as well as the transport demands between them.

Figure 22 shows the transport demand user form and the selections used to describe this case study. The bullet points will explain reasoning behind the selections in the context of the case study.



Figure 22: Case study demand user form

- **Commodity and Cargo Type:** The scope of this case study is to include LNG that is shipped only as liquid bulk cargo. It does not consider small, containerized parcels of

LNG that can be shipped via containership as this study is concerned with the traffic of LNG carriers (liquid bulk shipments) through the Panama Canal. It is assumed that volume of US Gulf LNG supply shipped by container will not have a significant impact on the volumes shipped as liquid bulk.

- **Service Type and Ship Type:** Liquid bulk LNG can be shipped via industrial shipped services or tramp shipping services. This study considers only the industrial shipping of LNG. This limitation can be made because it is likely that a majority of the Gulf LNG will be dedicated to long-term industrial shipping contracts. Liquid bulk LNG can only be shipped via LNG Carrier vessels.

- **Region and Country:** How the regions can be defined for a more comprehensive study. The region in this case is the Gulf of Mexico and the Asia-Pacific Region.

- **Origin and Destination:** This case study is concerned with the shipment of LNG from the Sabine Pass LNG production center to distribution centers in the Asia-Pacific and European markets. As seen in the user form, the Sabine Pass LNG terminal is selected as the only production center considered, while the selection of distribution center is "ALL DCs". This is because the program does not contain the functionality to individually select multiple distribution centers. Therefore, to model this scenario, only the distribution centers of interest to this case study can be included in the model data, as this selection will incorporate all distribution centers contained in the model data. The distribution center included in the model is the Senboku 1 LNG Terminal which has a location that is representative of all distribution centers in the Asia-Pacific Region.

The input selections made are then used to generate a list of all feasible transport demands. Figure 23 shows the results of the demand definition as they are output into the "Demand Alternatives" worksheet.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Feasible Demand Alternatives** | | | | | | | | | |
| 2 | Commodity name | PC name | DC name | Cargo Type | PCMode | DCmode | ShipType | Ocean Service Demand | Volume [million MT] | Time Span [days] |
| 3 | LNG | Sabine Pass LNG Terminal | Senboku 1 LNG terminal | Liquid bulk cargo | Direct | Direct | LNG Carrier | Industrial Shipping | 16 | 365 |

Figure 23: "Demand Alternatives" worksheet

## 10.3.2 Modeling the Supply for LNG Transport

Before the user forms are used to describe the supply that will fulfill the demand, the program must have the data relevant to the case study. Because, the distribution centers and supply centers are directly connected to the import and export ports, the supply elements that need data to describe them are the ports involved and the ocean services (ships) that will carry out the trade.

As mentioned, the services included in this study are meant to represent all LNG vessels that are Post-Newpanamax. A list of all ships that meet this criterion was generated by sea-web.com and uploaded to the model worksheets. Each ship was included in the model as a separate industrial service.

Figure 24 shows the transport supply user form and the inputs used to model the case study. The bullet points that follow will explain the reasoning behind the selections in the context of the case study.
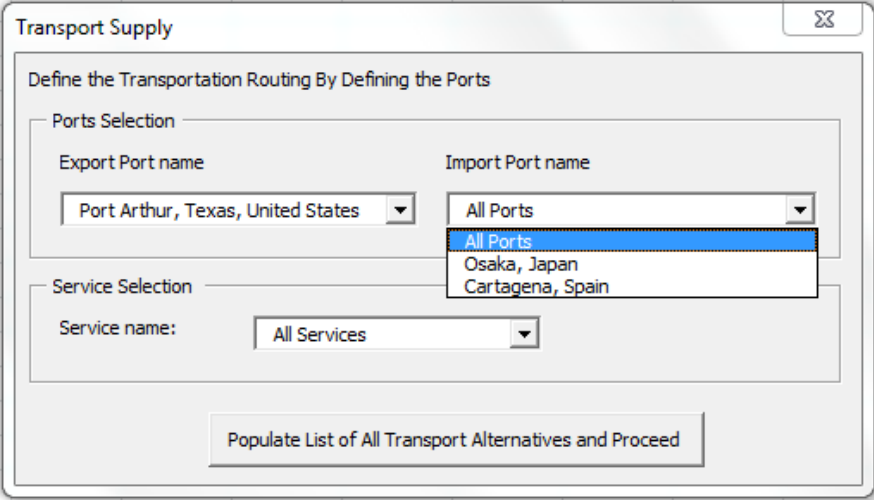


Figure 24: Casey study supply user form

- **Export port selection:** There is only one export port suited to meet the description of the cargo and the production center location which is Port Arthur, Texas, United States.

- **Import port selection:** Because there are multiple port destinations included in the model, the selection "All Ports" is made. Only the ports that suit the cargo description and distribution center location are included in the model.

- **Service selection:** To include all of the LNG vessels included in the model, the "All Services" selection is made.

The input selections made are then used to generate a list of all feasible transport supply. Figure 25 shows a portion of the results of the supply definition. Note that the only difference between the supply alternatives is the service.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | **Feasible Supply Alternatives** | | | | |
| 2 | **DC name** | **PC name** | **ExportPort name** | **ImportPort name** | **Service name** |
| 3 | Sabine Pass LNG Terminal | Senboku 1 LNG terminal | Port Arthur, Texas, United States | Osaka, Japan | AAMIRA |
| 4 | Sabine Pass LNG Terminal | Senboku 1 LNG terminal | Port Arthur, Texas, United States | Osaka, Japan | AL AAMRIYA |
| 5 | Sabine Pass LNG Terminal | Senboku 1 LNG terminal | Port Arthur, Texas, United States | Osaka, Japan | AL BAHIYA |
| 6 | Sabine Pass LNG Terminal | Senboku 1 LNG terminal | Port Arthur, Texas, United States | Osaka, Japan | AL DAFNA |
| 7 | Sabine Pass LNG Terminal | Senboku 1 LNG terminal | Port Arthur, Texas, United States | Osaka, Japan | AL GATTARA |
| 8 | Sabine Pass LNG Terminal | Senboku 1 LNG terminal | Port Arthur, Texas, United States | Osaka, Japan | AL GHARIYA |

Figure 25: "Supply Alternatives" worksheet

## 10.3 RESULTS

The results of this cost analysis yielded the required freight rate [USD/MMBtu][4] as a function of speed for each service, and therefore vessel, operating on an annual basis between the Gulf of Mexico and Osaka, Japan. Figure 26 shows the results of the cost calculation. The solid dark line represents the average RFR over the entire batch of vessels included in the analysis. The upper dark dotted line represents vessel with the maximum RFR and the lower dark dotted line represents the vessel with the minimum RFR.

The red lines represent the RFR of a New-Panamax LNG vessel with varying Panama Canal Tariff costs. Because of the current pricing differentials of natural gas between the US and the Asia-Pacific markets, the vessels are most profitable operating at their top speeds. Therefore, the plot shows that the Panama Canal tariff for an LNG vessel can be as high as 8.5 [USD/NT] before the largest LNG carriers transiting the Cape Horn route become a better economic solution.

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[4] MMBtu is a unit of natural gas and is the basis for how it is priced globally.
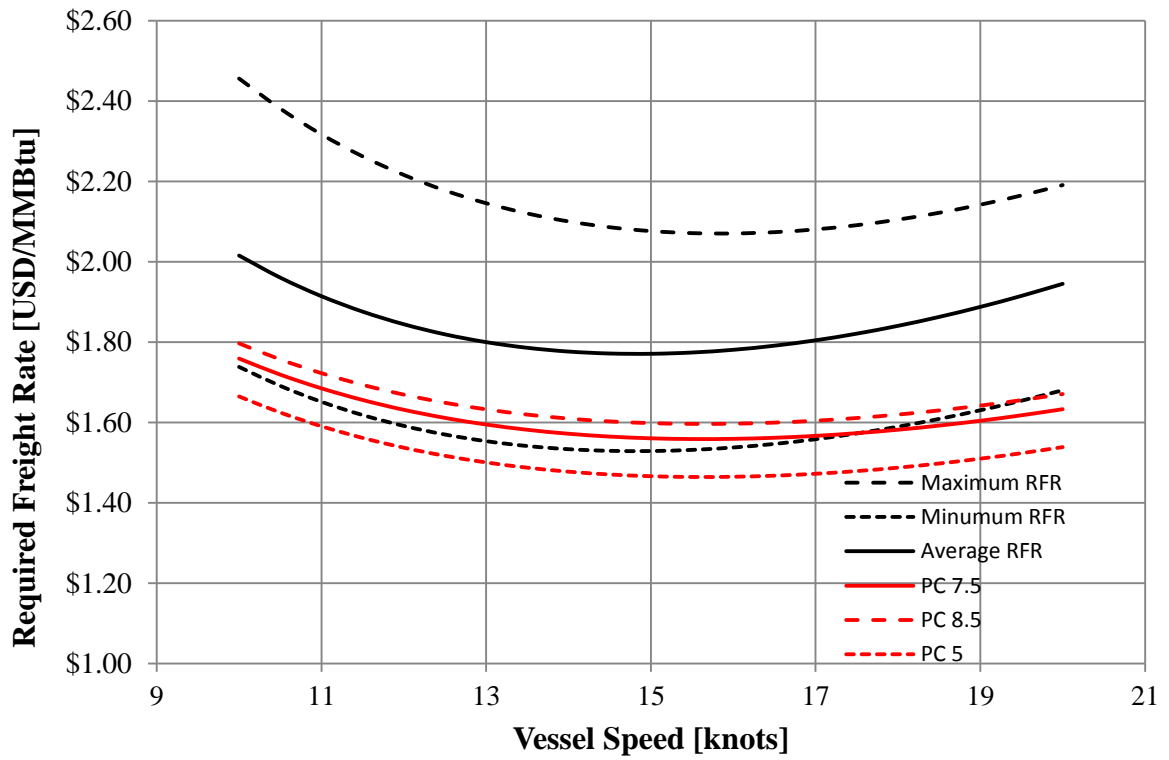
Figure 26: Post-Newpanamax RFR for LNG vessels operating between US Gulf & Japan

# 11. DISCUSSION

Although the generic model presents a valid core framework for modeling maritime freight transportation solutions, there are certain points where over-simplification may have hindered its ability to appropriately model certain transport scenarios. Another potential weak point with the generic model is its compatibility with transportation data that is generally available.

## 11.1 DATA COMPATIBILITY

A general issue with the model development methodology is that it did not consider the use of generally available maritime freight transportation data. The type and levels of demand aggregation included in the model were imposed to support the use of the model in certain analyses, and are not necessarily compatible with the data that is available for inclusion in the model. This same issue is present in the supply model as well. The modeling of supply is accomplished mainly by the inclusion of transport services in the model that are capable of meeting the demands. Although sufficient vessel data is generally available, to physically described the commercial fleet, it is difficult to find data that assigns this fleet to specific services, trades, or routes. The exception to this is Container liner shipping where services and schedules are generally publicly available.

## 11.2 POTENTIAL OVERSIMPLIFICATION ISSUES

### 11.2.1 Demand Modeling

Based on the background investigation into freight transportation modeling, it was determined that one of the requirements of the generic model was to support the use to disaggregate demand data. One of the main objectives of the demand aggregation was to characterize demand with the decision maker objectives in an effort to create better stake holder definition. The model was developed to handle this requirement by attaching a service type characterization to the demand descriptions. There are two potential issues with this methodology. First, it requires data to be uploaded to the model with a service type distinction, which may prove to be impractical for large volumes of demand data. Secondly, the service type distinction may not always capture the decision maker's (shipper's) actions appropriately. This is because although a shipper may demand a given service type, it does not automatically impose all of the characteristics of that service type to the demand. For instance, LNG shipping is largely dominated by what is typically characterized as industrial

shipping. This is because either the LNG buyer or seller is held responsible for supplying the transport of the LNG. However, they do not have to own or operate the vessels, as industrial shipping implies, to carry out the transport demand. Thus, the stake holder associated with the transport demand is definition is not appropriately. Although the shipper is still trying to minimize shipping costs, as implies by industrial shipping, the cost of shipping is not represented by the actual operation, capital, and voyage costs, but instead by the market chartering rates for LNG Carriers. Therefore the service type distinction of a cargo does not provide a clear way determining how the cost elements of a shipping operation should be handled. One potential solution to this is to make clear skate holder and cost element distinctions for the with regards to the relationship between the shipper and the service operator. However, this also runs into the issue of practical data availability.

## 11.2.2 Supply Modeling

The model uses a direct definition of services, their routes (ports of call), and the vessels that are used in the services to model the supply of maritime transportation. The main reasoning behind this is so that parameters related to the legs (speed and load factor) of the transport can be defined so the cost of a cargo movement can be estimated. This approach may be more suited for container shipping than for industrial or tramp shipping where the services may have dynamic routes (tramp ships following cargo) and variable fleets. If a service cannot be defined by fixed ports of call and the associated legs, the generic model cannot estimate the cost of the service operation. One potential solution to this is to define the performance of a service with yearly measured fleet data and allow the service to call all potential demanding ports. The cost of a specific measured cargo movement can then be estimated as an allocation of the total measured service performance.

## 11.2.3 Planning Levels

Although the generic model development paid consideration to analyses with different planning levels, the method of service definition creates certain limitations with regards to tactical planning problems, specifically fleet deployment. As discussed, service definition demands a trade definition with specified ports of call. This means that a fleet deployment problem can only be modeled is a service is included in the data multiple times to represent each alternative trade that a service can participate in. This represents a significant issue addressing fleet deployment problems for tramp shipping where there are generally no specified ports of call. One possible solution to this is to allow the service definition of a

tramp shipping service to include a range of feasible ports of call and an average distance from each.

In general, the model is not well suited for operational planning problems. This stems from the generic requirement of the model which inherently does not allow the inclusion of very specific parameters that are sometimes needed in operational planning problems. The generic model lends itself more to strategic planning model and analyses that require the assessment of vessel traffic flows.

## 11.2.4 VBA Modeling Tool

The implementation of the generic model into an MS Excel VBA program demonstrated that the generic model was supportable by a software solution. The case study demonstrated the practical use of the program in a real-world problem.

## 12. CONCLUSIONS

This thesis has presented a generic maritime freight transportation domain model, implemented in into a useful tool, and used the tool to perform a tactical planning problem dealing with the passage of LNG ships through the Panama Canal. The use of the model in the case study and further discussions have shown that the generic model has fulfilled its major requirements and represents a firm basis developing freight transportation models. The major shortcoming in the model involve its compatibility with available transport supply and demand data, the use of service type to capture stake holder definition and cost allocation, and the use of strict service definitions. Given these weaknesses, the generic model still provides a core framework that can be built upon to address problems where these weaknesses become significant concerns. The core functionality provided by the generic model that is key to its ability to act as a core framework is ability to generate feasible solutions based on either very specific or broad definitions of demand and supply variables.

## 13. RECOMMENDATIONS FOR FUTURE WORK

Although the generic model has been built to support the modeling of intermodal freight transportation, the inclusion of inland services and vehicles in the model is largely undeveloped. Therefore, it is suggested that inland services modeling should be developed and integrated into the model. This will allow the more realistic modeling of cargo movements of commodities and cargoes that typically have inland destination.

The implementation of the generic model into the MS Excel VBA tool has proved to be effective, but limited by the data uploading process. Therefore, it is suggested that a more user friendly and transparent method of uploading data to the model is developed.

The final suggestions for future work are to develop a more extensive performance measuring module (environmental performance, lifecycle cost, etc…), and develop compatibility with a variety of supply-demand matching methods and tools.

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# APPENDIX A: ROUTE SEGMENTCOST CALCULATION

Ocean Route Segment Cost (one-way, starting from loading and ending when unloaded at destination)

| Feasible Solution Parameters | Commodity name | |
|---|---|---|
| | CargoType name | |
| | ServiceDemand name | |
| | ShipType name | |
| | ExportPort name | Osaka, Japan |
| | ImportPort name | Port Arthur, Texas, United States |
| | Ship name | ZARGA |
| | Panama Canal | Disallow |
| | Suez Canal | |
| | restriction3 | |
| | restriction4 | |
| Routing Parameters | Total Distance | 15000 |
| | Junction 1 name | |
| | Junction 2 name | Punta Arenas, Chile |
| | Junction 3 name | |
| | Leg 1 Distance | |
| | Leg 2 Distance | 10000 |
| | Leg 3 Distance | 5000 |
| | Leg 4 Distance | |
| Service parameters | Leg speed | 20 |
| | Load factor | 0 |
| | ME Fuel Price [USD/mt] | 600 |
| | Aux Engine Fuel Price [USD/mt] | 600 |
| | Free parameter | |
| | Free parameter | |
| Activity Parameters | Unloading rate [m$^3$/hr] | 10000 |
| | Loading rate [m$^3$/hr] | 0 |
| | Mooring/Maneuvering time [hr] | 2 |
| | Fixed cost parameter [USD] | 1000 |
| | Variable cost parameter [USD/day] | 2000 |
| PortB Class Transport Activity Parameters | Unloading rate [m$^3$/hr] | 0 |
| | Loading rate [m$^3$/hr] | 10000 |
| | Mooring/Maneuvering time [hr] | 2 |
| | Fixed cost parameter [USD] | 1000 |
| | Variable cost parameter [USD/day] | 2000 |
| "Ships" Class Tranport Activity Parameters | Length [m] | 345,328 |
| | Breadth [m] | 53,8 |
| | Loaded Draft [m] | 12,2 |
| | Deadweight [mt] | 163922 |
| | Net tonnage (NT) [NT] | 51596 |
| | Vessel Capacity [m3] | 261104 |
| | Vessel service Speed [knots] | 19 |
| | Laden Vessel Propulsion Power at service speed [kW] | 37009 |
| | Ballast Vessel Propulsion Power as service speed [kW] | 27756,75 |
| | Aux power underway [kW] | 750 |

| | | |
|---|---|---:|
| | Aux power during cargo operations [kW] | 4000 |
| | Aux power idle in port [kW] | 500 |
| | ME Fuel Type name | IFO 380 |
| | Vessel ME Consumption [g/kW*hr] | 185 |
| | Aux Engine Fuel type | IFO 380 |
| | Aux engine consumption [g/kW*hr] | 190 |
| | Cargo Handling offloading [m3/hr] | 12000 |
| | Cargo handling loading [m3/hr] | |
| | Daily CAPEX [USD/day] | 55000 |
| | Daily OPEX [USD/day] | 10000 |
| | Free Parameter | |
| | Free Parameter | |
| "Junction" Class Transport Activity Parameters | Junction1 Additional Waiting time [hrs] | |
| | Junction1 Fixed cost parameter [USD] | |
| | Junction1 Variable cost parameter | |
| | Junction2 Additional Waiting time [hrs] | |
| | Junction2 Fixed cost parameter [USD] | |
| | Junction2 Variable cost parameter | |
| | Junction3 Additional Waiting time [hrs] | |
| | Junction3 Fixed cost parameter [USD] | |
| | Junction3 Variable cost parameter | |
| Voyage Time Calculation | Loading time [days] | 0,0 |
| | One-way time Sailing [days] | 31,3 |
| | Unloading time [days] | 0,0 |
| | Total Waiting [days] | 0,2 |
| | Total voyage time [days] | 31,4 |
| Calculation | Port fuel consmuption [mt] loading+unloading+waiting | 0,4 |
| | Sailing ME fuel consumption [mt] | 4491,9 |
| | Sailing AUX fuel consumption [mt] | 106,9 |
| | Total ME Fuel consumption [mt] | 4491,9 |
| | Total AUX Engine Fuel consumption [mt] | 107,3 |
| Transport Activity Calcultion | Transport Activity [$m^3$*nm] | 0 |
| Voyage Cost Calculation (VOYEX) | Fuel Cost [USD] | 2759497 |
| | PortA Fixed Cost [USD] | 1000 |
| | PortB Fixed Cost [USD] | 1000 |
| | PortA Variable Cost [USD] | 0,0 |
| | PortB Variable Cost [USD] | 0,0 |
| | Junction1 Fixed Cost [USD] | 0,0 |
| | Junction2 Fixed Cost [USD] | 0,0 |
| | Junction3 Fixed Cost [USD] | 0,0 |
| | Junction1 Variable Cost [USD] | 0,0 |
| | Junction2 Variable Cost [USD] | 0,0 |
| | Junction3 Variable Cost [USD] | 0,0 |
| | Total Voyage Cost [USD] | 2761497 |
| (OPEX) | Total Operating Cost [USD] | 314167 |
| (CAPEX) | Total Capital Cost [USD] | 1727917 |
| Total Route Segment Cost | Total Cost [USD] | 4803581 |

**APPENDIX B: REGION ASSIGNMENT CODE**

```vba
'DATA MANAGEMENT: REGION ASSIGNMENT TO INFRASTRUCTURE
Option Explicit
Option Base 1
Sub populateLocationRegionListSheets()
'The primary function of this sub-routine is to populate the
'Infrasturtucre lists with their location data and region based on the
'user region definitions
Application.ScreenUpdating = False

'variable definitions
    Dim i As Integer
    Dim j As Integer
    Dim k As Integer
    Dim t As Integer
    Dim z As Integer
    Dim p As Integer
    Dim dum As String
    Dim LocationListSheet As String
    Dim RegionToCountrySheet As String
    Dim CountryToLocationSheet As String
    Dim MapDataSheet As String
    Dim nlocations As Integer
    Dim Locations() As Variant
    Dim deg() As Double
    Dim min() As Double
    Dim sec() As Double
    Dim cardinaldirection() As String


'Complete for all infrastructures in the model
    For p = 1 To 5

    If p = 1 Then
    'List1:PortList_ALL
    'All ports
    LocationListSheet = "InfraList_ALL_PORT_ALL"
    RegionToCountrySheet = "RegionToCountry_ALL_PORT_ALL"
    CountryToLocationSheet = "CountryToInfra_ALL_PORT_ALL"
    MapDataSheet = "MapData_ALL_PORT_ALL"
    End If

    If p = 2 Then
    'List2: PCList_LNG
    LocationListSheet = "InfraList_LNG_PC_DIR"
    RegionToCountrySheet = "RegionToCountry_LNG_PC_DIR"
    CountryToLocationSheet = "CountryToInfra_LNG_PC_DIR"
    MapDataSheet = "MapData_LNG_PC_DIR"
    End If

    If p = 3 Then
    'List3: DCList_LNG
    LocationListSheet = "InfraList_LNG_DC_DIR"
    RegionToCountrySheet = "RegionToCountry_LNG_DC_DIR"
    CountryToLocationSheet = "CountryToInfra_LNG_DC_DIR"
    MapDataSheet = "MapData_LNG_DC_DIR"
    End If

    'List4: PortList_LNG_EXPORT_DIRECT
    'LNG EXPORT DIRECT PORTS
    If p = 4 Then
    LocationListSheet = "TerList_PORT_LNG_EXPORT_DIRECT"
    RegionToCountrySheet = "RegionToCountry_LNG_EXPORT_DIRE"
    CountryToLocationSheet = "CountryToPort_LNG_EXPORT_DIRECT"
    MapDataSheet = "MapData_Ports_LNG_EXPORT_DIRECT"
    End If

    'List5: PortList_LNG_IMPORT_DIRECT
    'LNG IMPORT DIRECT PORTS
    If p = 5 Then
    LocationListSheet = "TerList_PORT_LNG_IMPORT_DIRECT"
    RegionToCountrySheet = "RegionToCountry_LNG_IMPORT_DIRE"
    CountryToLocationSheet = "CountryToPort_LNG_IMPORT_DIRECT"
    MapDataSheet = "MapData_Ports_LNG_IMPORT_DIRECT"
    End If

'Populate the Locations array with the location information
```

```
'Convert the lat and long data to decimal values and
'return them to the sheet
    'select the sheet with the desired PC location data
    Sheets(LocationListSheet).Select

    'count the number of PCs
    Range("A2").Select
    nlocations = ActiveCell.Row
    Selection.End(xlDown).Select
    nlocations = ActiveCell.Row - nlocations + 1

    'populate the Locations array
    Range("A2").Select
    ReDim Locations(nlocations, 7) As Variant
        For i = 1 To nlocations
            For j = 1 To 4
            Locations(i, j) = ActiveCell.Value
            ActiveCell.Offset(0, 1).Select
            Next j
        ActiveCell.Offset(1, -4).Select
    Next i

    'Convert the longitude and latitude to deimcal values
    ReDim deg(nlocations, 4) As Double
    ReDim min(nlocations, 4) As Double
    ReDim sec(nlocations, 4) As Double
    ReDim cardinaldirection(nlocations, 4) As String
    For i = 1 To nlocations
        For j = 3 To 4
        deg(i, j) = Left(Locations(i, j), InStr(Locations(i, j), "°") - 1)

        min(i, j) = Mid(Locations(i, j), InStr(Locations(i, j), "°") + 1, _
        InStr(Locations(i, j), "'") - InStr(Locations(i, j), "°") - 1)

        sec(i, j) = Mid(Locations(i, j), InStr(Locations(i, j), "'") + 1, _
        Len(Locations(i, j)) - InStr(Locations(i, j), "'") - 2)

        cardinaldirection(i, j) = Right(Locations(i, j), 1)
        Next j
    Next i

    'Add the deimcal location values to the Locations Array
    For i = 1 To nlocations
        For j = 3 To 4
            Locations(i, j + 2) = deg(i, j) + (min(i, j) / 60) + (sec(i, j) / 3600)
            If cardinaldirection(i, j) = "S" Or cardinaldirection(i, j) = "W" Then
            Locations(i, j + 2) = Locations(i, j + 2) * -1
            End If
        Next j
    Next i

    'Output the Decimal Coordinates back to the data sheet
    'Clear the previous contents
    Range("E2:F2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents

    Range("E2").Select

    For i = 1 To nlocations
        For j = 5 To 6
            ActiveCell.Value = Locations(i, j)
            ActiveCell.Offset(0, 1).Select
        Next j
    ActiveCell.Offset(1, -2).Select
    Next i
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''''''''''''''''''''''
'Populate the regiondefinition array with the vertices of the global regions as definied
'by polylines
    Dim RegionDefinition() As Variant
    Dim npointsinregion() As Variant
    Dim nregions As Integer
    Call populateRegionDefinition(RegionDefinition, npointsinregion, nregions)
    'returns the RegionDefinition Array, the number of vertices in each region, and the
```

```vba
    'total number of regions

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''''''''''''''''''''''''''
'Use the winding number algorithm to find which locations lie in which region
    Dim latitude As Variant      'The decimal latatitude value of a given location
    Dim longitude As Variant     'The decimal longitude value of a given location
    Dim alpha() As Double        'The angle between the line segments created by connecting the loca
tion point to
                                 'adjacent vertices
    Dim totalangle() As Double   'The sum of all alphas for a region
    Dim theta1 As Double         'The angle created by the first line segment
    Dim theta2 As Double         'The angle created by the second line segment
    Dim quadtheta1 As Integer    'The quadrant of theta1
    Dim quadtheta2 As Integer    'The quadrant of theta2


    For t = 1 To nlocations     'Perform for all Locations
        latitude = Locations(t, 5) 'the latitude or location t
        longitude = Locations(t, 6) 'the longitude of location t

        'Check if location t lies in the a region
        ReDim alpha(nregions, 500) As Double
        ReDim totalangle(500) As Double
        For i = 1 To nregions     'Check each region
            'Find the directional angle between the port and adjacent region definition vertices
            'If the angles add up to 360 then the port lies within the region of interest
            'If the angles add up to 0 then the port lies outside of the region of interest
            'ccw is positive
            'cw is negative
            totalangle(i) = 0  'set the initial total angle to 0 before checking region i
            For j = 1 To npointsinregion(i) 'add angles for all nodes in the region
                If j = npointsinregion(i) Then 'for the last point

                    theta1 = Application.WorksheetFunction.Degrees _
                    (Application.WorksheetFunction.Atan2(RegionDefinition(i, j + 1, 2) - longitude, _
                    RegionDefinition(i, j + 1, 1) - latitude))

                    theta2 = Application.WorksheetFunction.Degrees _
                    (Application.WorksheetFunction.Atan2(RegionDefinition(i, 2, 2) - longitude, _
                    RegionDefinition(i, 2, 1) - latitude))

                    Else
                    'find the angle to the two points
                    theta1 = Application.WorksheetFunction.Degrees _
                    (Application.WorksheetFunction.Atan2(RegionDefinition(i, j + 1, 2) - longitude, _
                    RegionDefinition(i, j + 1, 1) - latitude))

                    theta2 = Application.WorksheetFunction.Degrees _
                    (Application.WorksheetFunction.Atan2(RegionDefinition(i, j + 2, 2) - longitude, _
                    RegionDefinition(i, j + 2, 1) - latitude))

                End If
                'Find the quadrant of theta1
                If theta1 > 90 Then
                    quadtheta1 = 2
                    Else
                        If theta1 > 0 Then
                            quadtheta1 = 1
                            Else
                            If theta1 < -90 Then
                                quadtheta1 = 3
                                Else
                                quadtheta1 = 4
                            End If
                        End If
                End If
                'Find the quadrant of theta2
                If theta2 > 90 Then
                quadtheta2 = 2
                Else
                    If theta2 > 0 Then
                    quadtheta2 = 1
```

```vba
                    Else
                        If theta2 < -90 Then
                        quadtheta2 = 3
                        Else
                        quadtheta2 = 4
                        End If
                    End If
                End If
                'get theta1 and theta2 relative to the positive x-axis
                If quadtheta1 = 1 Or quadtheta1 = 2 Then
                    theta1 = theta1
                    Else
                    theta1 = 360 + theta1
                End If

                If quadtheta2 = 1 Or quadtheta2 = 2 Then
                    theta2 = theta2
                    Else
                    theta2 = 360 + theta2
                End If

                'calculate all internal angles
                If quadtheta1 = 4 And quadtheta2 = 1 Then
                    alpha(i, j) = theta2 + (360 - theta1)
                Else
                    alpha(i, j) = theta2 - theta1
                End If
                If alpha(i, j) > 180 Then
                    alpha(i, j) = alpha(i, j) - 360
                End If
                If alpha(i, j) < -180 Then
                    alpha(i, j) = alpha(i, j) + 360
                End If
                'add up the angles for each region to see if they are 360
                totalangle(i) = totalangle(i) + alpha(i, j)
            Next j
            If totalangle(i) > 359.99 And totalangle(i) < 360.01 Then
                'If totalangle(i) = 360 Then add the Region to the Locations array
                Locations(t, 7) = RegionDefinition(i, 1, 1)
                'Make a list of regions with PC locations in them
                Exit For  'Exit the loop if the region is found
            End If
        Next i 'Check the next region if the location wasn't in the current one
    Next t 'move on to the next location


''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''''''''''''''''''''''''
'Output The Array to various sheets
    'Output the regions to the LocationListSheet
    Sheets(LocationListSheet).Select
    Range("G2").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents

    Range("G2").Select
        For i = 1 To nlocations
            ActiveCell.Value = Locations(i, 7)
            ActiveCell.Offset(1, 0).Select
        Next i

    'Output the Locations Array to the RegionToCountry Sheets
    Sheets(RegionToCountrySheet).Select
    Range("B3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents

    Range("B3").Select

        'populate the sheet with the Region names where locations exist
        'Get a unique list of the regions that have location in them
        'Also add "All Regions" to the list
            'collect all of the Regions
            Dim tempRegions() As Variant
            Dim Regions() As Variant
            ReDim tempRegions(nlocations) As Variant
```

```vba
    For i = 1 To nlocations     'check all locations
        tempRegions(i) = Locations(i, 7)
    Next i
    'get a unqie list
    Call UniqueItems(tempRegions, tempRegions, nregions)
    'put the list in alphabetical order
    Call alphabeticalBubble(nregions, tempRegions, tempRegions)

    'Add "All Regions" to the Regions array
    ReDim Preserve tempRegions(nregions + 1) As Variant
    ReDim Regions(nregions + 1)
    For k = 1 To nregions
        Regions(k + 1) = tempRegions(k)
    Next k
    'Add "All countries"-country at the top of the list
    nregions = nregions + 1
    Regions(1) = "All Regions"
    'output the list to the sheet
    For i = 1 To nregions
        ActiveCell.Value = Regions(i)
        ActiveCell.Offset(1, 0).Select
    Next i

'Populate the RegionToCountry Sheet with unique countries
'Also all "All Countries"
Dim tempRegionToCountry() As Variant
Dim RegionToCountry1() As Variant
Dim RegionToCountry2() As Variant
Dim ncountriesinregion() As Variant
Dim Numunique As Integer
ReDim RegionToCountry2(nregions, nlocations + 1) As Variant
ReDim ncountriesinregion(250) As Variant

For i = 1 To nregions  'do for all regions
    z = 1
    ReDim tempRegionToCountry(nlocations) As Variant
    If Regions(i) = "All Regions" Then
        For j = 1 To nlocations
            tempRegionToCountry(z) = Locations(j, 2)
            z = z + 1
        Next j
        Else
        For j = 1 To nlocations 'check all locations to see which ones belong to the region
            If Locations(j, 7) = Regions(i) Then
                tempRegionToCountry(z) = Locations(j, 2)
                z = z + 1
            End If
        Next j
    End If
    'get the unique list and output it to the RegionToCountry array
    Call UniqueItems(tempRegionToCountry, RegionToCountry1, Numunique)
    'Put tempRegionToCounry in Alphabetical order
    Call alphabeticalBubble(Numunique, RegionToCountry1, RegionToCountry1)
    'output the unique list to RegionToCountry2
    ncountriesinregion(i) = Numunique

    For k = 1 To ncountriesinregion(i)
        RegionToCountry2(i, k + 1) = RegionToCountry1(k)
    Next k
    'Add "All countries"-country at the top of the list
    ncountriesinregion(i) = ncountriesinregion(i) + 1
    RegionToCountry2(i, 1) = "All Countries"
Next i

'output the unique country list to the RegionToCountry sheet
Sheets(RegionToCountrySheet).Select
'clear the contents
Range("C3:C2000").Select
Range(Selection.End(xlToRight), Selection).Select
Selection.ClearContents

Range("B3").Select
For i = 1 To nregions
    For j = 1 To ncountriesinregion(i)
        ActiveCell.Offset(0, 1).Select
        ActiveCell.Value = RegionToCountry2(i, j)
```

```
        Next j
        'Selection.End(xlToLeft).Select
        ActiveCell.Offset(1, -ncountriesinregion(i)).Select
    Next i


'Output the Locations Array to the CountryToLocation Sheets
    'populate the CountryToLocation sheet with the region and country names
    Sheets(CountryToLocationSheet).Select
    'clear the contents
    Range("A3:B3").Select
    Range(Selection, Selection.End(xlDown)).Select
    Selection.ClearContents

    Range("A3").Select
    For i = 1 To nregions
        For j = 1 To ncountriesinregion(i)
            ActiveCell.Value = Regions(i)
            ActiveCell.Offset(0, 1).Select
            ActiveCell.Value = RegionToCountry2(i, j)
            ActiveCell.Offset(1, -1).Select
        Next j
    Next i

    'populate the CountryToLocation sheet with the Locations
    'clear the contents
    Range("C3:C2000").Select
    Range(Selection.End(xlToRight), Selection).Select
    Selection.ClearContents

    'the port needs to belong to both the region AND the country
    Dim tempregion1 As String
    Dim tempcountry1 As String
    Dim nlocationsincountryregion() As Variant
    ReDim nlocationsincountryregion(nregions, nlocations + 1) As Variant

    Range("A3").Select
    For i = 1 To nregions         'for all regions
        tempregion1 = ActiveCell.Value
        For j = 1 To ncountriesinregion(i)
            ActiveCell.Offset(0, 1).Select
            tempcountry1 = ActiveCell.Value
            nlocationsincountryregion(i, j) = 0

            If tempregion1 = "All Regions" Then
                If tempcountry1 = "All Countries" Then
                    For k = 1 To nlocations
                            ActiveCell.Offset(0, 1).Select
                            ActiveCell.Value = Locations(k, 1)
                            nlocationsincountryregion(i, j) = nlocationsincountryregion(i, j) +
1
                    Next k
                    ActiveCell.Offset(1, -nlocationsincountryregion(i, j) - 1).Select
                    Else
                    For k = 1 To nlocations 'search all locations
                        If Locations(k, 2) = tempcountry1 Then
                            ActiveCell.Offset(0, 1).Select
                            ActiveCell.Value = Locations(k, 1)
                            nlocationsincountryregion(i, j) = nlocationsincountryregion(i, j) +
1
                        End If
                    Next k
                    ActiveCell.Offset(1, -nlocationsincountryregion(i, j) - 1).Select
                End If
            Else
                If tempcountry1 = "All Countries" Then
                    For k = 1 To nlocations
                        If Locations(k, 7) = tempregion1 Then
                            ActiveCell.Offset(0, 1).Select
                            ActiveCell.Value = Locations(k, 1)
                            nlocationsincountryregion(i, j) = nlocationsincountryregion(i, j) +
1
                        End If
                    Next k
                    ActiveCell.Offset(1, -nlocationsincountryregion(i, j) - 1).Select
                    Else
```

```vba
                        For k = 1 To nlocations 'search all locations
                            If Locations(k, 7) = tempregion1 And Locations(k, 2) = tempcountry1 Then

                                ActiveCell.Offset(0, 1).Select
                                ActiveCell.Value = Locations(k, 1)
                                nlocationsincountryregion(i, j) = nlocationsincountryregion(i, j) + 1

                            End If
                        Next k
                        ActiveCell.Offset(1, -nlocationsincountryregion(i, j) - 1).Select
                        End If
                    End If
                Next j
            Next i

    'Output the location data to the MapDataSheet
        'populate the regions to the PortMapData2 sheet
        Sheets(MapDataSheet).Select
        Sheets(MapDataSheet).Cells.Clear
        Range("A1").Select
        ActiveCell.Value = MapDataSheet
        Range("A2").Select
        For i = 1 To nregions
            ActiveCell.Value = Regions(i)
            ActiveCell.Offset(0, 3).Select
        Next i

        'output the port name and longitude and latitude to PortMapData2
        Range("A2").Select
        For i = 1 To nregions
            z = 0
            tempregion1 = ActiveCell.Value
            ActiveCell.Offset(2, 0).Select
            For k = 1 To nlocations
                If Locations(k, 7) = tempregion1 Then
                    ActiveCell.Value = Locations(k, 1)
                    ActiveCell.Offset(0, 1).Select
                    ActiveCell.Value = Locations(k, 5)
                    ActiveCell.Offset(0, 1).Select
                    ActiveCell.Value = Locations(k, 6)
                    ActiveCell.Offset(1, -2).Select
                    z = z + 1
                End If
            Next k
            ActiveCell.Offset(-z - 2, 3).Select
        Next i
Next p
End Sub

Sub populateRegionDefinition(RegionDefinition, npointsinregion, nregions)
'Populate the regiondefinition array with the vertices of the global regions as definied
'by polylines
    Dim i As Integer
    Dim j As Integer
    Dim z As Integer
    'Dim nregions As Integer
    'Dim npointsinregion() As Variant
    'Dim RegionDefinition() As Variant
    Dim Hemisphere As Integer
    Dim cardinaldirection As String
    Dim deg1 As Double
    Dim min1 As Double
    Dim sec1 As Double

    'Select the sheet with the region definition data
    Sheets("RegionList").Select
    Range("A2").Select

    'count the number of regions
    nregions = ActiveCell.Column
    ActiveCell.Offset(0, 100).Select
    Selection.End(xlToLeft).Select
    nregions = ((ActiveCell.Column - nregions) + 2) / 2

    'count the number of points that define each region
    ReDim npointsinregion(nregions) As Variant
```

```
    Range("a3").Select
        For i = 1 To nregions
        npointsinregion(i) = ActiveCell.Row
        Selection.End(xlDown).Select
        npointsinregion(i) = ActiveCell.Row - npointsinregion(i) + 1
        ActiveCell.Offset(-npointsinregion(i) + 1, 2).Select
    Next i

    'populate the RegionDefinition array while also converting the lat and long to
    'decimal values
    ReDim RegionDefinition(nregions, 50, 2) As Variant
    Range("A2").Select
    For i = 1 To nregions
        RegionDefinition(i, 1, 1) = ActiveCell.Value
        ActiveCell.Offset(1, 0).Select
            For j = 2 To npointsinregion(i) + 1
                For z = 1 To 2
                    RegionDefinition(i, j, z) = ActiveCell.Value

                    deg1 = Left(RegionDefinition(i, j, z), _
                    InStr(RegionDefinition(i, j, z), "°") - 1)

                    min1 = Mid(RegionDefinition(i, j, z), _
                    InStr(RegionDefinition(i, j, z), "°") + 1, InStr(RegionDefinition(i, j, z), "'"
) _
                    - InStr(RegionDefinition(i, j, z), "°") - 1)

                    sec1 = Mid(RegionDefinition(i, j, z), _
                    InStr(RegionDefinition(i, j, z), "'") + 1, Len(RegionDefinition(i, j, z)) _
                    - InStr(RegionDefinition(i, j, z), "'") - 2)
                    cardinaldirection = Right(RegionDefinition(i, j, z), 1)

                    Hemisphere = 1
                        If cardinaldirection = "S" Or cardinaldirection = "W" Then
                        Hemisphere = -1
                        Else
                        Hemisphere = 1
                        End If
                    RegionDefinition(i, j, z) = (deg1 + (min1 / 60) + (sec1 / 3600)) * Hemisphere
                    ActiveCell.Offset(0, 1).Select
                Next z
                ActiveCell.Offset(1, -2).Select
            Next j
            ActiveCell.Offset(-npointsinregion(i) - 1, 2).Select
    Next i

    'Output the decimal regiondefinition polylines to the PortMapData sheet
    Sheets("PortMapDataRegions").Select
    Sheets("PortMapDataRegions").Cells.Clear
    Range("A1").Select
    ActiveCell.Value = "Region Definition Polylines"
    Range("a2").Select
    For i = 1 To nregions
        For j = 1 To npointsinregion(i) + 1
            For z = 1 To 2
                ActiveCell.Value = RegionDefinition(i, j, z)
                ActiveCell.Offset(0, 1).Select
            Next z
            ActiveCell.Offset(1, -2).Select
        Next j
        ActiveCell.Offset(-npointsinregion(i) - 1, 2).Select
    Next i


End Sub

'count the number of unique items
Sub UniqueItems(ArrayIn, uniquelist, Numunique)
'    Accepts an array or range as input
'    If Count = True, the function returns the number of unique elements
'    If Count = False, the function returns a variant array of unique elements
    Dim Unique() As Variant ' array that holds the unique items
    Dim Element As Variant
    Dim i As Integer
    Dim FoundMatch As Boolean
'    Counter for number of unique elements
```

```
    Numunique = 0
'   Loop thru the input array
    For Each Element In ArrayIn
        FoundMatch = False
'       Has item been added yet?
        For i = 1 To Numunique
            If Element = Unique(i) Then
                FoundMatch = True
                Exit For '(exit loop)
            End If
        Next i
AddItem:
'       If not in list, add the item to unique list
        If Not FoundMatch And Not IsEmpty(Element) Then
            Numunique = Numunique + 1
            ReDim Preserve Unique(Numunique)
            Unique(Numunique) = Element
        End If
    Next Element
'   Assign a value to the function
    uniquelist = Unique

End Sub

'Bubble Sort for string arrays
Sub alphabeticalBubble(n, a, b)
'sorts an array in ascending order using the bubble sort
'n is the number of values in the array
'a is the input array
'b is the output array
Dim m As Integer, i As Integer
Dim switch As Boolean
Dim dum As Variant
For i = 1 To n
    b(i) = a(i)
Next i
m = n - 1
Do              'loop through the passes
    switch = False
    For i = 1 To m 'loop through the array
        If Asc(Left(UCase(b(i)), 1)) > Asc(Left(UCase(b(i + 1)), 1)) Then
            dum = b(i)
            b(i) = b(i + 1)
            b(i + 1) = dum
            switch = True
        End If
    Next i
    If switch = False Then Exit Do
    m = m - 1
Loop
End Sub
```

**APPENDIX C: ROUTE GENERATION CODE**

```
'DISTANCE AND JUNCTION CALCULATOR
Option Explicit
Option Base 1

Sub PortToPortRoutes(PortA, PortB, RoutingOptions_sort_canal, noptions)
    Dim PortName() As Variant
    Dim PortToJunction() As Variant
    Dim PortToNjunctions() As Variant
    Dim PortToPort() As Variant
    Dim PortToNports() As Variant
    'Import the Distance Data from the excel sheet
    Call ImportDistData(PortName, PortToJunction, PortToPort, PortToNjunctions, PortToNports)

    Dim i As Long
    Dim j As Long
    Dim Distance_direct As Long
    Dim PortANum As Integer
    Dim PortBNum As Integer
    Dim m As Long
    Dim n As Long
    Dim switch As Boolean
    Dim dum As Variant
    Dim z As Long
    Dim a As Integer
    Dim b As Integer
    Dim c As Integer
    Dim junc1 As String
    Dim junc2() As String
    Dim x As Integer

    Dim Junction1Num() As Integer
    Dim Junction2Num() As Integer

    Dim junction1() As String
    Dim junction2() As String
    Dim Distance1() As Integer
    Dim Distance2() As Integer
    Dim Distance2_final() As Integer
    Dim Distance3() As Integer
    Dim TotalDistance() As Integer
    Dim njunctions_temp(50) As Integer
    Dim RoutingOptions() As Variant


'Search for a direct connection
    'search for PortA index
    For i = 1 To UBound(PortName)
        If PortName(i) = PortA Then
        PortANum = i
        Exit For
        End If
    Next i

    'search for PortB in PortToPort()
    For j = 1 To PortToNports(PortANum)
        If PortToPort(PortANum, j, 1) = PortB Then
        Distance_direct = PortToPort(PortANum, j, 2)
        Exit For
        End If
    Next j

    'search for PortB in PortToJunction()

    For j = 1 To PortToNjunctions(PortANum)
        If PortToJunction(PortANum, j, 1) = PortB Then
        Distance_direct = PortToJunction(PortANum, j, 2)
        Exit For
        End If
    Next j
'Implement more layers of searching
    ReDim junction1(PortToNjunctions(PortANum) + 1) As String
    ReDim Junction2out(PortToNjunctions(PortANum) + 1) As String
    ReDim Distance1(PortToNjunctions(PortANum) + 1) As Integer
    ReDim Distance2_final(PortToNjunctions(PortANum) + 1) As Integer
    ReDim Distance2(PortToNjunctions(PortANum) + 1, 50)
```

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    ReDim Distance3(PortToNjunctions(PortANum) + 1, 50) As Integer
    ReDim TotalDistance(PortToNjunctions(PortANum) + 1) As Integer
    ReDim Junction1Num(PortToNjunctions(PortANum) + 1) As Integer
    ReDim junction_2(PortToNjunctions(PortANum) + 1, 50) 'there will be a second junction for each junction connected to PortA
    ReDim Junction2Num(PortToNjunctions(PortANum) + 1, 50) As Integer

For j = 1 To PortToNjunctions(PortANum) 'for all junctions of PortA
junction1(j) = PortToJunction(PortANum, j, 1) 'assign each junction to junction1
Distance1(j) = PortToJunction(PortANum, j, 2) 'assign each junction distance to distance1
    For i = 1 To UBound(PortName) 'find the index number for the current junction
        If Application.WorksheetFunction.Proper(PortName(i)) = junction1(j) Then 'find the index number for the current junction1
        Junction1Num(j) = i

            For z = 1 To PortToNports(Junction1Num(j))  'for all ports connected to junction 1
                If PortToPort(Junction1Num(j), z, 1) = PortB Then 'if PortB is connected to current junction1 then assign distance2
                Distance2_final(j) = PortToPort(Junction1Num(j), z, 2)
                Exit For
                End If
            Next z
                If Distance2_final(j) = 0 Then
                    'populate list of all junctions connected to junction 1 for junc2
                    njunctions_temp(j) = 0    'counter for the number of junction2s connected to a given junction1
                    For a = 1 To PortToNjunctions(Junction1Num(j)) 'for all junctions connected to junction1
                    junction2(j, a) = PortToJunction(Junction1Num(j), a, 1) 'select the second junction name
                    Distance2(j, a) = PortToJunction(Junction1Num(j), a, 2) 'select the second junction distance

                        For b = 1 To UBound(PortName) 'find the index number for the current junction
                            If Application.WorksheetFunction.Proper(PortName(b)) = junction2(j, a) Then 'find the index number for the current junction
                            Junction2Num(j, a) = b
                                For c = 1 To PortToNports(Junction2Num(j, a)) 'for all ports connected to junction2
                                    If PortToPort(Junction2Num(j, a), c, 1) = PortB Then 'if PortB is connected to current junction2 then assign distance2
                                    Distance3(j, a) = PortToPort(Junction2Num(j, a), c, 2)
                                    Exit For
                                    End If
                                Next c
                            Exit For
                            End If
                        Next b
                    'count the number of junction2s in each junction1
                    njunctions_temp(j) = njunctions_temp(j) + 1
                    Next a
                End If
        Exit For
        End If
    Next i
Next j


'output a list of potential routing options
ReDim junc2(200) As String
ReDim RoutingOptions(100, 10) As Variant
Dim resultcount(100) As Variant          'count the number of results in each category
Dim nresults As Integer
Dim y As Integer

i = 1
    If Distance_direct <> 0 Then
            RoutingOptions(i, 1) = PortA
            RoutingOptions(i, 2) = Distance_direct
            RoutingOptions(i, 7) = PortB
            RoutingOptions(i, 8) = Distance_direct
            junc1 = RoutingOptions(i, 3)
            i = i + 1
    End If
```

```
    c = 1
    For j = 1 To PortToNjunctions(PortANum)
        If Distance2_final(j) <> 0 Then  'if there is a potential to go to Junction1 then save it
        junc2(c) = junction1(j)
        c = c + 1
        End If
        If Distance2_final(j) <> 0 And junc1 <> PortB Then
            RoutingOptions(i, 1) = PortA
            RoutingOptions(i, 2) = Distance1(j)
            RoutingOptions(i, 3) = junction1(j)
            RoutingOptions(i, 4) = Distance2_final(j)
            RoutingOptions(i, 7) = PortB
            RoutingOptions(i, 8) = Distance1(j) + Distance2_final(j)
            i = i + 1
        End If
    Next j


    For j = 1 To PortToNjunctions(PortANum)
        If Distance2_final(j) = 0 Then
                For a = 1 To njunctions_temp(j)
                    x = 0
                    If Distance3(j, a) <> 0 Then
                        For z = 1 To c
                            If junction2(j, a) = junc2(z) Then
                            x = x + 1
                            End If
                        Next z
                        If x = 0 Then
                                RoutingOptions(i, 1) = PortA
                                RoutingOptions(i, 2) = Distance1(j)
                                RoutingOptions(i, 3) = junction1(j)
                                RoutingOptions(i, 4) = Distance2(j, a)
                                RoutingOptions(i, 5) = junction2(j, a)
                                RoutingOptions(i, 6) = Distance3(j, a)
                                RoutingOptions(i, 7) = PortB
                                RoutingOptions(i, 8) = Distance1(j) + Distance2(j, a) + Distance3(j
, a)

                                i = i + 1

                        End If
                    End If
                Next a
        End If
    Next j

nresults = i - 1



'put the results in order
'sort the array with bubble sort
Dim RoutingOptions_sort(50, 8) As Variant

For i = 1 To nresults
    For j = 1 To 8
    RoutingOptions_sort(i, j) = RoutingOptions(i, j)
    Next j
Next i
m = nresults - 1
Do                                          'loop through passes
    switch = False
    For i = 1 To m  'loop through the array
        If RoutingOptions_sort(i, 8) > RoutingOptions_sort(i + 1, 8) Then
            For j = 1 To 8

            dum = RoutingOptions_sort(i, j)
            RoutingOptions_sort(i, j) = RoutingOptions_sort(i + 1, j)
            RoutingOptions_sort(i + 1, j) = dum

            Next j

            switch = True
        End If
    Next i
```

```
    If switch = False Then Exit Do
    m = m - 1
Loop


'get rid of the duplicate options based on minimum distance
For i = nresults To 1 Step -1
    For j = i - 1 To 1 Step -1
    If RoutingOptions_sort(i, 5) = RoutingOptions_sort(j, 5) And RoutingOptions_sort(i, 5) <> "" An
d RoutingOptions_sort(i, 8) >= RoutingOptions_sort(j, 8) Then
        For z = 1 To 8
            RoutingOptions_sort(i, z) = ""
        Next z
    Exit For
    End If
    Next j
Next i

'Control the panama canal or suez canal options
'This is not used
Dim AllowPanama As Boolean
Dim AllowSuez As Boolean

AllowPanama = True
AllowSuez = True

If AllowPanama = False Then
    For i = 1 To nresults
        For j = 2 To 6
        If RoutingOptions_sort(i, j) = "Panama, Panama" Then
            For z = 1 To 8
            RoutingOptions_sort(i, z) = ""
            Next z
        End If
        Next j
    Next i
End If

If AllowSuez = False Then
    For i = 1 To nresults
        For j = 2 To 6
        If RoutingOptions_sort(i, j) = "Port Said, Egypt" Then
            For z = 1 To 8
            RoutingOptions_sort(i, z) = ""
            Next z
        End If
        Next j
    Next i
End If

ReDim RoutingOptions_sort_canal(50, 8) As Variant
'get rid of the blanks
z = 1
For i = 1 To nresults
    If RoutingOptions_sort(i, 1) <> "" Then
        For j = 1 To 8
        RoutingOptions_sort_canal(z, j) = RoutingOptions_sort(i, j)
        Next j
        z = z + 1
    End If
Next i

'get the actual number of results
noptions = 0
For i = 1 To nresults
    If RoutingOptions_sort_canal(i, 1) <> "" Then
    noptions = noptions + 1
    End If
Next i
'display results
Sheets("RouteOptions").Cells.Clear
Sheets("RouteOptions").Select
Range("a1").Select
For j = 1 To nresults
    c = 0
```

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    For z = 1 To 8
    ActiveCell.Value = RoutingOptions_sort_canal(j, z)
    ActiveCell.Offset(0, 1).Select
    c = c + 1
    Next z
    ActiveCell.Offset(1, -c).Select
Next j

End Sub
Sub ImportDistData(PortName, PortToJunction, PortToPort, PortToNjunctions, PortToNports)
'This sub-routine imports the data from the distance tables into various arrays
Application.ScreenUpdating = False

Dim firstcell As String
Dim i As Integer
Dim j As Integer
Dim z As Integer
Dim nrows As Long
Dim nports As Long
Dim maxjunctions As Integer
Dim maxports As Integer

'count the number of rows and the number of ports
firstcell = "a1"
Sheets("PortToJunction_Ocean").Select
nrows = Range(firstcell).Row
Range("a5000").Select
Selection.End(xlUp).Select
nrows = ActiveCell.Row - nrows + 1
nports = (nrows + 1) / 2

'populate PortName() with the list of ports
Range(firstcell).Select
ReDim PortName(nports) As Variant
For i = 1 To nports
    PortName(i) = ActiveCell.Value
    ActiveCell.Offset(2, 0).Select
Next i

'populate PortToNjunctions() with the number of junctions in each port
Range(firstcell).Select
ActiveCell.Offset(0, 1).Select
ReDim PortToNjunctions(nports) As Variant
For i = 1 To nports
    ActiveCell.Offset(0, 500).Select
    Selection.End(xlToLeft).Select
    PortToNjunctions(i) = ActiveCell.Column - 1
    ActiveCell.Offset(2, -PortToNjunctions(i) + 1).Select
Next i


'populate PortToNports() with the number of ports in each junction
Sheets("PortToPort_Ocean").Select
Range(firstcell).Select
ReDim PortToNports(nports) As Variant
For i = 1 To nports
    ActiveCell.Offset(0, 500).Select
    Selection.End(xlToLeft).Select
    PortToNports(i) = ActiveCell.Column - 1
    ActiveCell.Offset(2, -PortToNports(i) + 1).Select
Next i

'populate PortToJunction() and PortToPort() with the ports and junctions connected to each port
    'find the maximum Njunctions for any port to dimension the PortToJunction() array
        maxjunctions = 0
        For i = 1 To nports
            If PortToNjunctions(i) > maxjunctions Then
            maxjunctions = PortToNjunctions(i)
            End If
        Next i
    'find the maximum Nports for any port to dimension the PortToPort() array
        maxports = 0
        For i = 1 To nports
            If PortToNports(i) > maxports Then
            maxports = PortToNports(i)
            End If
```

```
        Next i

    'populate PortToJunction() array with junction names and distances
    Sheets("PortToJunction_Ocean").Select
    Range(firstcell).Select
    ActiveCell.Offset(0, 1).Select
    ReDim PortToJunction(nports, maxjunctions, 2) As Variant
        For i = 1 To nports
            For z = 1 To 2
                For j = 1 To PortToNjunctions(i)
                    PortToJunction(i, j, z) = ActiveCell.Value
                    ActiveCell.Offset(0, 1).Select
                Next j
            ActiveCell.Offset(1, -PortToNjunctions(i)).Select
            Next z
        Next i

    'populate PortToPort() array with port names and distances
    Sheets("PortToPort_Ocean").Select
    Range(firstcell).Select
    ActiveCell.Offset(0, 1).Select
    ReDim PortToPort(nports, maxports, 2) As Variant
        For i = 1 To nports
            For z = 1 To 2
                For j = 1 To PortToNports(i)
                    PortToPort(i, j, z) = ActiveCell.Value
                    ActiveCell.Offset(0, 1).Select
                Next j
            ActiveCell.Offset(1, -PortToNports(i)).Select
            Next z
        Next i
End Sub
```

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'CALLS DISTANCE CALCULATOR TO POPULATE DISTANCE AND JUNTION TABLES
Option Explicit
Option Base 1
Sub populatePortToPortRoutessheet()
'This sub routine populates the  routes (leg distance and junction sheets)
'between deep-sea ports using ocean shipping
    Application.ScreenUpdating = False
    Dim i As Long
    Dim j As Long
    Dim k As Long
    Dim z As Long
    Dim PortA As String    'PortA (starting port) name
    Dim PortB As String    'PortB (ending port) name
    Dim PortToPortRoutes_full() As Variant
    Dim nPortsA As Integer
    Dim nPortsB As Integer
    Dim PortAList() As Variant
    Dim PortBList() As Variant
    Dim AllPorts() As Variant
    Dim sheetname As String
    Dim indexnumber As Integer
    Dim RouteOptions() As Variant
    Dim noptions As Integer

'populate the PortA array with all portA in the model
    Call populateInfraList_LNG_EXPORT_DIR 'only need to do this if it is a stand alone procedure
            'Public InfraList_LNG_EXPORT_DIR() As Variant
            'Public nLNG_EXPORT_DIR As Integer
            'Public nLNG_EXPORT_DIR_col As Integer

'populate the PortB array with all PortB in the model
    Call populateInfraList_LNG_IMPORT_DIR 'only need to do this if it is a stand-alone procedure
        'these are the outputs of the above sub routine
            'Public InfraList_LNG_IMPORT_DIR() As Variant
            'Public nLNG_IMPORT_DIR As Integer
            'Public nLNG_IMPORT_DIR_col As Integer

'Define the infrastructures

    PortAList = InfraList_LNG_EXPORT_DIR
    nPortsA = nLNG_EXPORT_DIR

    PortBList = InfraList_LNG_IMPORT_DIR
    nPortsB = nLNG_IMPORT_DIR


'make an array that holds a list of all of the ports (PortAs and PortBs)
ReDim AllPorts(nPortsB + nPortsA)
For i = 1 To nPortsA
    AllPorts(i) = PortAList(i + 1, 1)
Next i

For j = 1 To nPortsB
    AllPorts(i) = PortBList(j + 1, 1)
    i = i + 1
Next j

Dim resultscounter As Integer

'Use the Distance calculator to populate array with port to port distances and junctions for all co
mbinations
ReDim PortToPortRoutes_full(nPortsA + nPortsB, nPortsA + nPortsB, 20)
resultscounter = 0
    For i = 1 To nPortsA + nPortsB  'for all ports in the calculations
        For j = i To nPortsA + nPortsB 'only need to do the upper half of the matrix
            PortA = UCase(AllPorts(i))
            PortB = Application.WorksheetFunction.Proper(AllPorts(j))
            'call the distance calculator
            If UCase(PortA) <> UCase(PortB) Then
                Call PortToPortRoutes(PortA, PortB, RouteOptions, noptions)
                    Sheets("RouteList_Ocean").Select
                    Cells((resultscounter + 2), 1).Select
                    For k = 1 To noptions
                        For z = 1 To 8
                        ActiveCell.Value = Application.WorksheetFunction.Proper(RouteOptions(k, z))
                        ActiveCell.Offset(0, 1).Select
```

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                        Next z
                        ActiveCell.Offset(1, -8).Select
                        resultscounter = resultscounter + 1
                    Next k
                End If
            Next j
        Next i

'include the reverse direction in the list
    Cells(resultscounter + 2, 1).Select
     For i = 2 To resultscounter + 1
         For j = 7 To 1 Step -1
             ActiveCell.Value = Cells(i, j).Value
             ActiveCell.Offset(0, 1).Select
         Next j
             ActiveCell.Value = Cells(i, 8).Value
         ActiveCell.Offset(1, -7).Select
     Next i




'The meaning of the last dimention index numbers in PortToPortRoutes_full
'1 = porta name
'2 = leg1 distance
'3 = junction1 name
'4 = leg 2 distance
'5 = junction2 name
'6  = leg 3 distance
'7 = portb name
'8 = total distance


End Sub
```