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Review

A Critical Review of a Holistic Model Used for Assessing Multimodal Transport Systems

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Abstract: The purpose of this paper is to present a rigorous and critical review of an established cost/time-distance model. The model offers a perspective on the inter-relationships between transport modes, nodes, methods and cargo volumes, types and forms. Organisations can review their door to door supply chain costs by applying the model described in the paper. The reviewed multimodal transport cost model is based on a relatively simple framework but demonstrates that other existing models of modal choice, multimodal transport and inventory location all oversimplify the transport process. The critical components of the model are the transport from origin to destination, consignment loading/unloading, intermodal transfer and performance variability. Other activities such as storage, value addition and customs clearance can be added into the model as required. Several findings emerge from the development of the model and provide much greater clarity concerning the cost-structure of door-to-door multimodal transport services along economic corridors. The model is shown to be a useful tool for identifying theoretical alternative locations for facilities such as inland terminals. The relative unit costs of operating respective freight transport modes lead to a series of classic door-to-door cost profiles stemming from the modal mix, which varies according to shipment distance, volume, cargo value-density and other variables.

Keywords: modal choice; cost model; multimodal transport; supply chain; intermodal transfer

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1. Introduction

The globalisation of production and the demand for low-cost sourcing over the last three to four decades have led to greater demands for the physical movement of goods, and in parallel a need for the transfer of associated information. Movements of raw materials, semi-finished or finished goods are dynamic, and the 'postponement' of some processes often moves them closer to the customer. The transport of goods over long distances balances availability, increases choice and matches supply with demand. In parallel, sophisticated logistics and supply chain management systems have been developed to support supply networks.

Thus, freight transport is a fundamental aspect of balancing time and space and reducing unit costs. This is most observable on international routes where scale-economies are important. The methods of transport, the multimodal nature of many supply chains and the supporting infrastructure have therefore become increasingly sophisticated and diverse. Generally, the longer the transport distance, the more complex the solutions become, and trading protocols involving cargo owners, facilitators and transporters need to be regularly reviewed in order to adjust to technological developments and global trading dynamics [1].

International freight transport can range in scale from only a few to many thousands of kilometres. At close proximities transport methods may be unsophisticated, e.g., through the use of unimodal transport making use of existing infrastructure to bridge a small gap between the supplier and a customer. Over longer distances, at a regional or international scale, transport solutions become more varied with formal procedures and control protocols.

Such control mechanisms are designed to facilitate intra-regional freight movements, and many trading blocs (EU, ASEAN and NAFTA are examples) attempt to facilitate the free movement of goods without compromising security and control.

Generally, over the last 70 years, although there have been several incremental technological improvements, freight transport has been reasonably stable, with evolutionary rather than revolutionary growth. It is likely that greater change will come over the next few decades but the fundamental basis that the majority of transport is a derived demand supporting other activities will remain. However, developing more efficient supply chains balancing the use of low-geared maritime transport, high-geared airfreight linked by intermodal road and rail transport to exploit economies of scale will likely continue, and transport solutions will need to be flexible in order to be able to respond to demand variations, technological developments and an increasing politicisation of trade [2]. It is in this context that this paper seeks to offer a perspective on how international multimodal transport can be best understood and more effective solutions developed.

The continuous increase in pressure on supply chains over the last decade and the advent of COVID-19 during the past year has led to the performance and efficiency of supply chains being brought into increasingly sharp focus. By extension, therefore, the research into modal supply chain capability and robustness is now arguably more important than ever before.

This manuscript seeks to examine the match between theoretical portrayals of multimodal transport in logistics chains and the real-time operation of such chains. A cost-time-distance model, originally developed in the 1990s, is used as the core theoretical framework for the discussion. The model has transport at its core, but it is flexible enough to accommodate a wide range of other parameters including, for example, capacity, ownership, speed, cost/tonne, reliability, stock holding, inventory cost/kg and the volumes, types and forms of the cargo itself.

The purpose and structure of this paper is therefore to review how the model has been used, and how it might continue to be used in the future. The aim is to demonstrate how an established multimodal transport model could be developed from its current operations-based form into a sophisticated tool with high potential value at a strategic level, which would aid policymakers and planners involved in the broader logistics field.

Initially developed as a descriptive operations-management tool for blueprinting transport corridors from a distance, time, cost and modal choice point of view, the second-level use of the model is essentially tactical. The blueprinting process enables operators to evaluate, for instance, the quickest, shortest, cheapest or "best" route and modal mix at a given point in time. At a strategic level, however, the model can aid policymakers in steering, for example, carbon-minimising or continuous improvement strategies.

Mathematical modelling including forecasting and optimisation could be employed in tandem with the cost model. This would enable commercial metrics such as inventory management or strategic stockholding algorithms to be used for both present-state analysis and for future scenario-building along the lines of "what if" modelling.

The aim of this paper is thus to take a more holistic approach and to further develop the model's level of sophistication in order to capture the full range of inputs affecting transport and logistics solutions, especially over long distances and for complex international routes.

2. Method

A literature review is a critical analysis of the body of knowledge related to a specific topic or research question and provides the reader with a picture of the state of knowledge, along with the main questions in the subject area which are being investigated [3]. Further, a literature review is an extensive critique of the literature on a given research topic and will need to contain a critical analysis and integration of information from a number of sources, as well as consideration of any gaps in the literature and possibilities for future research [4,5]. Thus, when research is conducted, a literature review is an essential part of the research because it covers previous research undertaken on the topic, and provides a platform on which the current research is based [6].

The purpose of such a critical review is to examine the corpus of theory that has accumulated with regard to an issue, concept, theory, or phenomenon. A critical literature review helps to establish which theories already exist, the relationships between them, to what degree the existing theories have been investigated, and to develop new hypotheses to be tested. A critical review may identify a lack of appropriate theories, or reveal that current theories are inadequate for explaining new or emerging research problems. The unit of analysis can focus on a theoretical concept, a whole theory, or even a conceptual framework [7]. The critical review conducted in this paper uses a multimodal transport/cost/time model developed in the 1990s, initially developed under the United Nations Development Programme (UNDP), and subsequently by the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) as the unit of analysis. The application of the model is in both academic assessments of real-time cargo movements, and also in the contemporary assessment of corridors for a range of businesses. The paper is therefore of value for private operators, international organisations and policy makers in their decision making in the field of international trade and transport flows. The analysis shows the development of the use of the model from its initial development for operational assessments, through its use for more tactical considerations to its more recent focus as a strategic tool.

3. Findings

3.1. Traditional Approaches to Modal Choice

It has long been recognised that transport is a key activity within logistics [8–14] and that, in turn, successful transport operations can be critical to supply chain efficiency both for inbound freight, such as components supply, and outward finished products distribution. For short-distance transport, especially internal land-based transport, solutions are usually clear-cut and simple; but over medium to long hauls modal combinations can be varied and complex [15]. In these cases, elements such as cost, capacity, convenience, reliability and practicality are considered together in a series of trade-offs; the door-to-door benefits of road haulage are thus compared with the qualities of a range of possible multimodal transport solutions [16,17]. Over long to very long distances, however, a wide range of influences come into play in determining freight routeing, and mode, method and carrier choice. The economies of the respective transport modes: air, sea, waterway, rail and road, form the basic framework for freight carriage and for supply chain structure optimisation from a transport perspective [18–20].

Indeed, the ever-decreasing pro rata unit costs over time of shipping, derived primarily from steadily increasing ship size and from parallel developments in cargo unitisation and containerisation, have been cited as decisive components in the globalisation of the world economy [21].

It has been noteworthy, however, that the development of theory of intermodal or multimodal transport provision has received much less attention than its practical application. This is especially true of the portrayal of the economic theory, which underpins the concepts of, respectively, modal choice and modal combination. Several underlying principles determine the roles of transport modes:

- The balance of fixed versus variable costs
- Modal characteristics, including networks, vehicles and regulatory regimes
- Economies of scale and the cube law

The 'cube law' states that the volume or capacity of a ship increases in proportion to the cube of its dimension, whereas its fuel consumption is a function of its resistance through the water which is itself proportional to its frontal surface area, or the square of its width dimension. Thus, from a fuel-carrying point of view, a ship can theoretically be of any size. The advent and spread of containerisation, which greatly facilitated large-scale shipment of general cargo over long distances, led to the adoption of systems which were entirely different from those which were dominant hitherto [9,21]. Put simply, the methods of transport were revolutionised and transport and logistics research suddenly began to follow a new path.

Rather than focusing on modal competition, emphasis is now placed on how modes could best combine to produce least-cost, least-distance or least-time solutions; more subtly, solutions could now also involve 'packages' that could be tailored to particular requirements. Despite this revolutionary change in transport techniques, the literature has lagged behind with the emphasis still on modal choice [10] road-rail competition [22,23] intermodality [9] and modal indifference [23] or on inventory management, or supply chain management.

3.2. Risk in Modal Choice

A separate branch of the literature covers risk, which captures commercial risks in the form of loss, damage and delay. At first glance, this could be closely linked to insurance premia, but this is not the case because:

1. there are some forms of risk which are not likely to be covered by insurance premia [24]; and
2. insurance premia usually relate more to the claims record of the insured rather than to the actual risk of using a specific route, mode or method.

The early work of Sharp [25] shed further light on the significance of damage risk in this context. Blauwens and Van de Voorde [26] looked at the underlying decision-making process in choosing between using road haulage or inland waterway in continental Europe. No assessment of loss, damage or delay was made, but they confirmed that time-savings were valued much more highly than the role of working capital [22]. Likewise, Kaatama [27] highlighted key considerations in the movement of goods (general freight, timber products, metals, paper) imports and exports, showing that financial cost persists as the most important consideration, but speed, service reliability and, in some cases damage can be almost as important. Baumol and Vinod [24] developed a 'modal indifference curve' which enabled the attributes of different modes to be evaluated in a simple trade-off analysis. They showed that, for example, if rail is slower than road it should not be cheaper; if air is faster than ship it should be more expensive and so on. Fowkes et al. [22] took a willingness to pay approach, which was somewhat similar, but more sophisticated. Although they only considered road versus rail, they looked at a wide commodity range from high value/low density to low value/high density. By varying the distance and volume, they examined how willing a potential customer is to pay more to receive goods more quickly. Conversely, they modelled how much less a customer would expect to pay for a slower service. More recently work by Kwak et al. [24] has considered the implications of risk in international supply chains.

Conventional and early approaches to modal decision-making can be synthesised and visually presented as in Figure 1. As can be seen from this synthesis, it is apparent that the 'trade-offs' were treated in what would seem to be an over-simplistic way, for example volume against value or weight against volume. What such approaches did not consider in a sophisticated way was that other factors may have also formed an important consideration in any decision that was made, for example how critical was time in the overall supply chain process.

A further dimension which needs greater consideration, and which is not implicitly included in the synthesis outlined in Figure 1 which relates to commercial decision-making, is that of humanitarian crises and emergency conditions. In such situations, and other crisis contexts, perhaps most recently exhibited with the COVID-19 global pandemic, is the need to accommodate considerable variations and departures from standard responses. The works by Christopher and Tatham [28] and Tatham and Christopher [29,30] drew together a wide range of material which discusses the response required in emergency situations created by natural events such as earthquakes, droughts and tsunamis, among others. Specific consideration of adaptations to multimodal supply chains have been undertaken by, for example, Beresford and Pettit [31] and Al Hashimi et al. [32]. More recently, a work by Nikolopoulos et al. [33] added an additional dimension by developing a forecasting approach to disasters which could contribute to a more robust appreciation of the parameters it is necessary to account for in crisis situations.

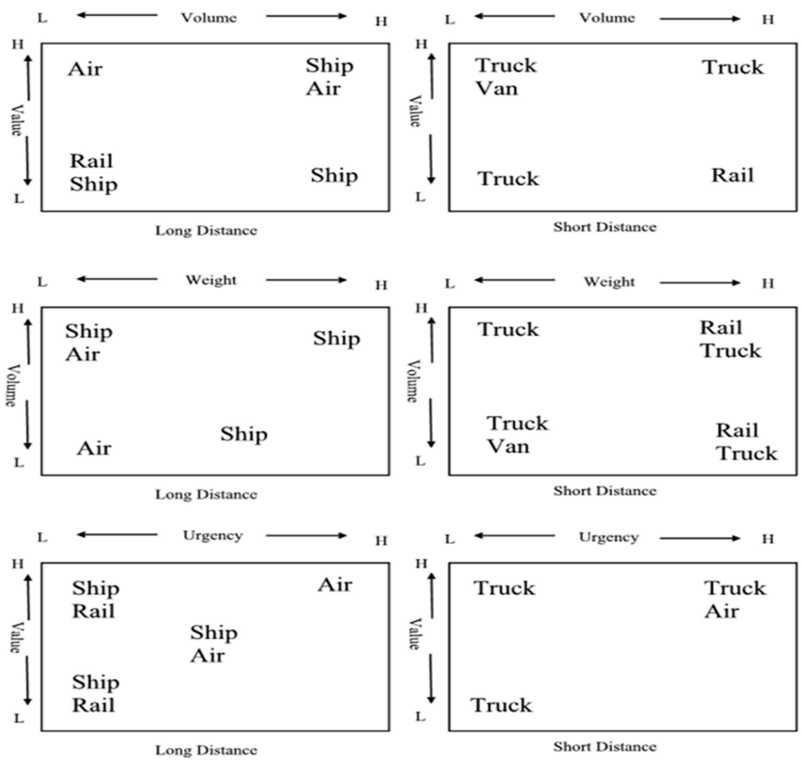

Figure 1. Synthesis of modal decision-making. (*Source:* Adapted from McKinnon, 1989 [3]).

3.3. The Advent of a New Approach

The increasing interest in trade facilitation and transport liberalisation through the 1980s gave birth to a large body of literature [9,18,21,34] and the first attempts emerged to fuse the economists' approach [26] with a multimodal viewpoint taken by transport geographers [21]. Early development work as shown in Figure 1 identified very little except the transport modes, and the potential for there to be interchange points between modes. This was used as a foundation onto which detail was added. The most obvious second layer of detail is probably the ports and inland terminals, as they form a logical link between theory and practice. Beresford [15] took a case study approach, following whisky exports from Scotland, UK, to Greece, and this enabled specific details to be formally added to develop a more comprehensive model for the first time as shown in Figure 2.

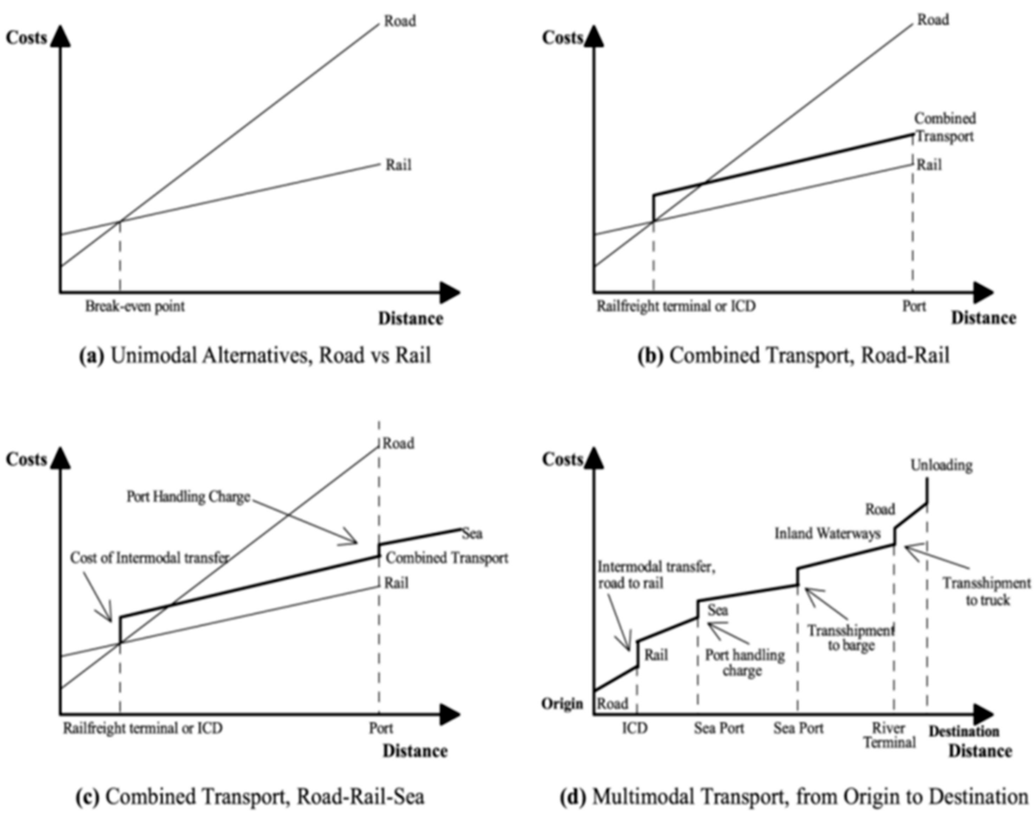

Figure 2. Multimodal transport cost model (*Source:* Adapted from Beresford [15]).

While inland terminals should be located at, or close to, the point where the economic competitiveness of one transport mode gives way to another, this is not simple, as discussed earlier; cargo volumes, cargo value-density, supply chain gearing and other factors complicate the picture considerably [10,35]. Even site specificities such as land availability, site shape and planning constraints play a critical role, with the result that this theoretical locational optimum for intermodal terminals is very difficult to achieve. Within the transport and cargo-handling or transfer step in the model there are many sub-components of the operation which could be separated out and, potentially, presented in the model. Port or terminal operating costs and transport costs especially lend themselves to more detailed treatment if required.

All methods of transport, whether passenger or freight, involve some effort (and hence implicitly cost) to provide and load the vehicle and, of course, to gain access to the relevant infrastructure. This start-up process can be envisaged as a vertical step in the curve with the height of the step being proportionate to the start-up cost. It is widely acknowledged that the bundle of costs enabling start-up is substantially greater for rail than for than for road transport but, conversely, provided the relevant load carrying units are well-utilised, there is a significant cost-saving per tonne-kilometre or per-passenger kilometre by using rail vis-à-vis road [22] over a certain distance. In any event, the road and rail operating cost curves can be envisaged as a start-point for a more inclusive model.

The first re-examination of the classic 'road versus rail approach' taken by [22] was by Beresford and Dubey [36]. The focal point of their study was the development of 'Dry Ports' or Inland Container distribution hubs as an integral part of trade expansion and modal integration. Thus, the literature, hitherto mostly restricted to a road/rail debate, was extended to embrace sea and inland waterway transport.

Several new and pertinent issues emerged when this attempt to capture the key characteristics of the four main surface transport modes in this way:

- How should the angles of slope of the respective modes relate to each other?

- Should the x and y axes be drawn to the same scale?
- How high should the vertical steps be at the loading/unloading and interchange points?
- Should the interchange points have a 'realism' such that each should stand for a terminal, depot or port where freight interchange takes place in reality?
- Should the lines representing movement be straight or curved?
- Should the diagram follow the full logistics chain from origin to destination or should it focus only on outward or inward segments?
- Could the key parameters of cost, time and distance all be portrayed, or should the variable be paired into cost vs. distance and time vs. distance?

In practice, as the theory of multimodal transport is complex, it cannot be viewed as a simple extension of traditional bimodal models such as those suggested by Baumol and Vinod [23], or Fowkes et al. [22]. It is proposed that distance, time and cost should be considered as secondary and, as such, they can be invoked as an overlay to the main model. McKinnon [10] suggested 30 additional variables and, though the list lacks sophistication and it is certainly not exhaustive, these remain good candidates for 'secondary variables'. In accordance with situation and need, these could in turn be split and again a number of studies have attempted this in the context of, for example, port logistics [37]. These studies shed considerable light on how the cost/time/distance model should be constructed and developed; four further key aspects need to be considered as below.

3.4. Angle of Slope

Empirical evidence points strongly towards trucking or road haulage, operating costs ranging from $1 per kilometre in an open-road uncongested environment over medium distances to $2 per kilometre over short distances or in congested environments [38]. This would convert to 10–20 cents per tonne-kilometre or 10–20 pence per tonne-mile for laden average-to-large trucks. If distances are very short, especially in urban stop-start conditions, operating costs would be higher still resulting in a steeper slope angle [17].

Trucks are also legally constrained in terms of length, width, height and overall gross weight, and by driver's work hours. This effectively 'lids' the output of the vehicle in terms of maximum tonnage or volume transportable in a given time period [17]. In the model under development here, the relationship between trucking costs and distance can be taken as linear, but in reality there is some reduction in costs pro rata with distance, implying that the line representing truck operating costs should curve to reflect the slight attenuation of costs with distance. The variation in operating conditions by location, time of day, country etc., would make this unworkable, however, and the portrayal of the distance-costs relationship as a straight line is deemed acceptable for clarity and to avoid spurious or unnecessary complexity.

In the model, road transport is the natural start-finish mode, and it is thus represented by a comparatively steeply-angled line to reflect its relatively high operating costs in standard conditions. Shipping costs, on the other hand, are well known to be extremely low for large, well-utilised vessels (for example, the early work of Pearson and Fossey [39], and contemporary studies such as Stopford [19]). Ship operating costs of just a few cents per tonne kilometre, container-mile or container-kilometre are regularly quoted [19,40], and this has an obvious implication for the portrayal of shipping costs in the model. However, it should be noted that, in the same way that larger trucks tend to be deployed for the longest distances, and smaller trucks are generally used for local freight collection and distribution, the largest vessels are used on the large volume, long distance trades.

This has remained true for decades [19] despite an obvious and clear trend towards ever-larger ships on most of the main trade lanes. As is the case for truck deployment, it is likewise true that smaller ships serve lower-volume trades, sail shorter distances and require smaller ports. The logistics of container shipping per se often therefore resolve into a 'hub and spoke' system with the smaller feeder ships in effect servicing the larger 'mother' vessels at hub or load-centre ports; there is an extremely large literature on this [37] but the subject of shipping network structures lies outside the scope of this paper. For decades, seagoing vessels in virtually all sectors have become inexorably larger, at least until external constraints such as port water depth or canal width have been reached [19,41]. For the transport cost-model, it is therefore clear that the shipping leg in a multimodal transport operation will be portrayed by a shallow angled line reflecting a slow accumulation of cost with distance per unit carried. In some cases (shipping over very long distances with very large vessels) the curve could approach the horizontal; that is to say, unit costs per kilometre or per nautical mile would be extremely low. For smaller vessels, e.g., tramp ships or feeder ships, the unit costs will clearly be higher and thus translates into a steeper angle for the shipping cost line in the model.

For both rail and waterway transport, the carrying capacity is limited by the dimension and tractive power constraints. In the case of rail, virtually all major networks work to strict loading gauge limits which specify maximum height and width of the freight (or passenger) carrying unit. The lengths of individual wagons are typically 60–80 feet (18–25 m); this is again constrained by, see, for example, overhang when cornering. Wagon widths are limited to 2.5–3 m, mostly by platform and furniture clearance, and again cornering cut-in. In summary, wherever rail freight services operate the trains are ultimately constrained volumetrically by limits on train height and width; weight carrying is also constrained by motive power capability and axle weight loadings. Internationally, the volumetric and weight-carrying capabilities of freight railways are clearly very variable; trains can be comparable to feeder ships in capacity and cost per-tonne kilometre, but often they are configured for agility as much as for capacity to suit modern logistics requirements with high running speeds with medium sized trains. The result is that, on many routes, 100–130 kilometres per hour (65–80 miles per hour) with 50–100 containers is seen as close to optimum at least on heavily-utilised UK/European networks [42]. Such constraints are formalized in inter-regional or pan-regional legal frameworks.

For the cost model under discussion here, this clearly implies that, provided that distances are long enough and volumes large enough, unit costs of rail freight operations should be substantially lower pro-rata than trucking but significantly more expensive than shipping in most cases. The transport-cost line for rail should therefore be portrayed exhibiting an angle which is somewhere between that for road-haulage and that for shipping. However, intermodal movements involving road-rail combined transport must include a cost step in the model to acknowledge the effort put in and costs incurred in the intermodal transport operation.

Canal or inland water transport is similarly characterised by a combination of some unconstrained dimensions and some which are constrained. In practice, the mix of these varies according to region, type of waterway, seasonal factors, whether or not the waterway is bridged and local regulatory regimes. Lloyd's Maritime Atlas [43] and Lloyd's Ports of the World [41] summarise the navigational features and dimensional limits of the longer waterways of the world. For inland waterborne transport to adequately compensate for its slow operational speeds and its inability to offer door-to-door services, volumetric and weight carrying capabilities have to be substantially greater, perhaps an order of magnitude greater than those of trucks [16].

As is the case for freight trains, inland waterway vessels vary considerably in size, reflecting both local physical constraints and levels of demand. Research suggests that vessel draughts of around 9 feet (2.5 m) are required for large-scale, effective and competitive water transport [41,43]. Similarly, vessel beam, length and air draught constraints should not be so tight as to limit carrying capability (and vessel stability) to a level that, locally, trucking is more effective and lower cost [44]. In extremis, inland navigation is virtually unconstrained, e.g., on the Amazon where seagoing vessels with a draught of 11+ meters can sail in any season as far as Manaus [43]. On major European rivers, vessels with a draught 3 m and more, carrying 2000 tonnes of cargo are commonplace and the regulatory regime (e.g., banning truck operation at weekends over certain routes) strongly favours inland navigation [45].

Translating this complex mix of variations into a generality for the cost model, the steepness of the waterway cost curve will almost invariably be less than that of the trucking curve, but it will be steeper than the open-sea shipping curve. Whether its steepness is greater than, or less than that of the rail curve, will depend on particular physical, regulatory and commercial criteria, especially capacity utilisation. In the same way that rail terminals are very rarely available at cargo origins/destinations, so inland waterway ports are seldom true origins or destinations; in the model therefore, the waterway cost curve, like the rail curve should stop short of the vertical axis. For both rail and waterway, the precise logistics circumstances will ultimately determine how the cost curves should be portrayed in this regard.

3.5. The Cost Step

The unimodal approach to transport choice in logistics is fundamentally flawed in the area of modal interaction. Even the paper by Frejinger et al. [46], which evaluates the environmental footprints of transport operations in Europe, fails to portray modal interchange accurately; rather, road, rail and waterway transport are portrayed in isolation. In reality, most, if not all, long supply chains are multimodal and at least one interface between modes is a critical component both of the chain structure itself and of the model development.

The theoretical model initially proposed by Beresford and Dubey [31] saw its first application in the study of European container logistics by Hosley and Beresford [47]. This captured both the freight movement (ship, road, rail) components and the intermodal transfer components (at ports or inland terminals) and scaled them according to cost. It emerged that port handling charges for containerised freight are typically 2–4 times as high as charges levied at inland terminals where infrastructure, equipment and manning costs appear to be much less; in the model therefore the cost step at the ports will typically be 2–4 times as high as the 'step' at inland terminals. At both locations, no material progress along the supply chain is made, but there may be value-addition or inventory management opportunities [13]. This has clear implications for complex multimodal chains both in the abstract and in the field: for a chain to be competitive, the economics of transferring freight between modes must be at least equaled by the cost/time savings or other benefits gained by using the additional mode or modes.

Where shipments are intercontinental, i.e., they involve land-sea or land-air combinations of necessity, many 'cost-steps' can be observed [48]. Jung [48] compared the Far East–Europe landbridge route with the shipping route using the framework under discussion here and demonstrated that the number of times a vessel or a train stops at intermediate points en-route can be critical in determining the competitive position of each route against the other. Furthermore, he showed that the total time spent at rail terminals (land bridge route) or ports (shipping routes) can be greater than the movement time if trains or ships stop even fairly frequently for cargo pick-up/drop-off. In the model, this is visibly evident from the large number of cost steps in the progress line, and the height of the steps give an at-a-glance view of the relative handling costs at respective terminals. In turn, this gives a first indication of each terminals' efficiency relative to the others along the route.

3.6. Scaling

The model depends fundamentally on an x/y comparison. Although x, y and z axes could be utilised and the model could therefore be presented in 3 dimensions, its value is probably greatest in pair-wise form. Classically, cost versus distance, and time versus distance invite comparison, but it could be contended that in many logistics environments, distance per se is not in itself important: rarely do logisticians, or the cargo owners, worry too much about distances shipments actually cover. It could be argued, however, that distance data should be obtained first to establish an invariant base for comparison. The early works of Pearson and Fossey [39] and Hayuth [9] demonstrate that, in landbridge operations at least, distances are critical to the relative competitiveness of the shipping and rail-based alternatives. Pearson and Fossey [39] refer to this critical distance measure as the 'convexity ratio'.

On the other hand, it has widely been accepted that as goods become more valuable, time criticality increases, especially where shipments are tied into a manufacturing or assembly process. The very structure of logistics, especially the transport component, intimately ties certain costs, at least partly, to time (through driver's wages) and other cost to distance (through vehicle fuel consumption). There is, therefore, a very strong argument for taking a pair-wise approach; thus distance/cost, time/distance or time/cost, are most easily handled in the model. The recent Freight Best Practice case studies published by the UK Government's Department for Transport, which focus on multimodal transport solutions for internal and international freight consignments, confirm the practical value of this approach [49]. Whether distances matter or not, the model is flexible enough to employ a numeric scale or not, as preferred.

3.7. The 'Confidence Index' and Performance Variability

Banomyong and Beresford [35] widened the reach of the cost model, and increased its value, by including a 'confidence' index. Though crude, this provided a significant advancement as it demonstrated the roles not only of the quantifiable commercial elements of alternative routes in an international supply chain, but also of the 'softer' influences on decision-making. The focus of this research was the export of textile products from Indo-China to Europe, and various routeing options at the supply end were examined. Although the differences between the routes were not large, the cost-time-distance model gave the study the disciplined framework it needed for maximum clarity.

UNESCAP [50,51] followed a similar disciplined path in the rigorous examination of, respectively, trade routes linking Indo-China with central Asia, and overland trade between the Far East and Europe. These studies pushed the application of the cost model into yet more geographical areas, but perhaps more importantly, they developed the confidence index by following a 'best performance–worst performance' approach to corridor analysis. In this way, the model had now embraced supply chain variability in its framework and the disciplined approach followed by the model provides the opportunity to measure performance against the same parameters (Figure 2).

4. New Dimensions: Supply Chain Ownership, Environmental Footprint

The structure of the time/cost-distance model can be tested against real conditions in a range of circumstances; at the centre of the model's logic is the relative operating costs and the fixed costs of necessary infrastructure provision for the respective transport modes. It is therefore pertinent to consider both classic, or typical, operational conditions and extreme cases in order to validate the model in as robust a way as possible. Two snapshots of typical conditions were provided in the papers by Beresford [15] and Banomyong and Beresford [35] discussed above. These cover respectively; a long, complex land/sea supply chain which offers a variety of mode and route combinations and alternatives, and a very long shipping dominated chain which offers routeing and modal alternatives only near the origin and destination. Further recent studies have widened the scope and range of the model validation process. These studies have covered a variety of cargoes over varying distances, as detailed in Table 1, summarising the characteristics of the trade which influence choice of route, mode and method.

Table 1. Selected Applications of the Multimodal Transport Time/Cost Model.

Supply Chain	Product	Dominant Mode	Feeder Options	Key Factors
Scotland–Greece [15]	Whisky	Road/Sea	Road	High value density. Heavy. Non perishable. Fragile. Medium volume.
Lao PDR–EU [35]	Garments	Sea	Road	High value density. Non-perishable. Non-fragile. Medium Volume.
New Zealand–China [52]	Milk Products	Sea	Road	Medium value density. Perishable. High Volume.
Taiwan–China [44]	Flowers	Sea	Road/Ferry	Vulnerability to damage/deterioration. Trade barriers. Alternative route options
Eire–China [53]	Automatic Telling Machines	Air/Sea-Air	Road	High value density. Heavy low volume. Valuable as return cargo.
Australia–China [54]	Iron Ore	Sea	Rail/Road	Very high volume. Low value. Alternative land modes as reserve.
France–South Africa [55]	Containerised products	Sea	Road/Waterway	Mixed cargo. Unitised. Brokering of cost versus speed.
Germany–Kazakhstan [56]	Mining Equipment	Rail	Road	High Value, Low Volume
Kazakhstan–Iran [57]	Grain	Rail/Sea	Road	Medium Value. High Volume
Europe–Iraq [32]	Humanitarian Aid	Sea	Road/Rail	High intrinsic value. Medium Volume

Sources: Developed from Beresford [15]; UNESCAP [50].

All represent typical regular freight flows undertaken by bulk cargo specialists, mainstream container shipping companies, unit load specialists and inland logistics service providers as appropriate. The diversity of cargo types, transport forms, value-densities, regularity of shipment and special characteristics such as fragility align well with the factors shown to influence modal choice by, for example, McKinnon [10]. All of the above cases make use of conventional trucks for 'first mile' and/or 'last mile' collection/delivery or for a longer part of the logistics chain according to need. Invariably, the trucks' capacities are in the region of, if not precisely, one to two TEU (one FEU). The feeder vessels and barges e.g., those used in the flowers and plants trade between Taiwan and China, carry 40–50 FEU (80–100 TEU), the deep-sea maritime container vessels operating between the Far East and Europe currently mostly carry 15–20,000 TEU and the European block trains typically run with 50–100 TEU over the long routes [17]. The larger European container barges carry 100–200 containers; by comparison, the longest of the North American container trains carry the equivalent of 300 to 400 TEU, though often in a complex mix of conventional and over-length, over-height boxes. The economics of the respective modes, judged by their typical carrying capacities at least, would therefore appear to be further confirmation of the logic of the cost-time-distance model examined here. The relative efficiencies of the modes can also be viewed from an extreme case perspective (Table 2); this enables and additional rule of thumb cross check on the validity of the angles of slope for the different transport modes to be carried out.

Table 2. Capability of transport modes.

Trucks
The largest trucks ever built, the specialist 97 m long ore-carrying Australian road trains operate at around 400 tonnes overall gross weight on dedicated mine-to-terminal routes. They are however constrained as they operate at the limits of current tractive power capability, being around ten times as heavy as standard road-going trucks in many countries [17].
Trains
Worldwide, freight trains are almost all less than 5 m (17 feet) in height with just a few notable exceptions such as the network of double-stack container and triple-deck car carrying rail services in United States–Canada–Mexico, the ultra-high (7 m) Channel Tunnel Shuttle trains, UK – France, the rolling road piggy-back services in Germany and through-Alpine tunnels, and the Finland–Russia passenger-motor rail trains [17]. The length of freight trains, which can easily be varied to suit freight volumes and logistics demands, is arguably one of their major assets with 1–1.5 mile long container trains common in North America on coast-to-coast routes. Equipped with multiple power units, freight trains in South Africa/Australia run up to 40,000 tonnes all-up weight.
Ships
The largest ships, the Ultra Large Crude Carriers, have long been operating at 400,000+ deadweight.
Operating Ratios
Given the above maximum tonnage limits, the road: rail: ship ratios are conveniently 1: 100: 1000. These ratios should provide clues to modelling the maximum vehicle size of each mode and hence cost portrayal in a hypothetical 'maximum limit' case.

As Banomyong and Beresford [35] suggested, transit time versus cost versus variability are amongst the key trade-offs in the transport and logistics industry. Multimodal transport systems give us the opportunity to examine the trade-offs and to present them numerically. Especially interesting is the way the model enables the trade-offs to be visualised. In reality, operators often hedge their route and mode choices in order to broker several carriers against one another and to reduce risk [28], hence the cost-time trade-off would not be pure. However, operators often re-evaluate their distribution strategies annually or towards the end of a contract period in order to attain the best modal and carrier combination. The products vary widely in terms of their value–density and other characteristics. In all cases several modal combinations are available and within each mode a number of different carriers offer similar or slightly differentiated services. The decisive factors involved in the time-cost and other trade-offs are suggested.

In the 2000s, a generic form of the model, enabling the user to dissect both the intermodal transfer components and the transport or movement elements, was made available on the UNESCAP website (https://www.unescap.org/resources/timecost-distance-methodology (accessed on 26 February 2021)). The availability of the model on the UNESCAP website allowed the model to become a reference tool for transport and logistics policy makers in the assessment of economic corridors. A significant number of assessments have been undertaken and a summary of those conducted over the last decade are shown in Table 3. The table shows how the model has been developed from its original conception as a method of assessing the operational characteristics of a transport chain to the more nuanced use as a tool to assist both tactical decision making and strategic policy development.

Table 3. Operational, Tactical and Strategic Applications of UNESCAP Time/Cost/Distance Methodology, 2010–2020.

Date	Approach *	Scope	Region
2020	O, T	Reconfigured corridor performance toolkit	Global
2019 **	O, S	Measuring sustainable development goals: an inclusive approach	Global
2019	O, T, S	Blueprinting corridor performance in East Africa [ongoing]	Sudan, Kenya, Djibouti, Somalia, Ethiopia, Uganda
July 2018	S	EN panel discussion, ESCAP- CAREC Institute, Baku, Azerbaijan	Central Asia
March 2018	O, S	UNESCAP study on Eurasian transport corridors; Ankara, Turkey	Eurasia
April 2017	T, S	Trade and Transport monitoring – Think Asia [ongoing]	Nepal, Asia
January 2017	S	Asian Development Bank – Business and Economics	Asia
2016	O, T	Supply Chain Management for Humanitarians; A tool for identifying barriers	Global
July 2016	T, S	Trade and Transport monitoring mechanism	Australasia, Africa, Central Asia, Indo-China
2015	O, S	World Bank's Logistics Performance Index [ongoing]	Global
September 2015	T, S	Trade and Transport Facilitation Monitoring Mechanism, UNNEXT, Moscow	Russia, Eurasia
2015	T, S	Customs and Trade facilitation, national competitiveness, food security	UK, Global
2014	T, S	International transport solutions and food security in Africa	Africa
2014	O, T, S	Trade and Transport Corridor Management Toolkit, World Bank [ongoing]	Global
August 2014	T, S	Asia-Pacific Trade Facilitation Forum	Asia-Pacific
2014	T, S	Central Corridor, East Africa. Transit Transport Facilitation Agency	East Africa
July 2014	O, T	Rwanda road transit. Survey of northern and central corridors	East Africa
May 2014	O, T	Corridor performance toolkit–regional applications [ongoing]	Global
April 2014	S	Trade and transport facilitation monitoring mechanism (workshop)	Nepal
March 2014	S	Trade and transport facilitation monitoring mechanism (workshop)	Bhutan
February 2014	S	First corridor meeting: Kazakhstan; Kyrgyzstan, Tajikistan	Central Asia
2012	T, S	Tajikistan's transit corridors and their potential for developing regional trade	Central Asia
2011	O, S	Middle East and the Arab world–Action Plan for Safer and More Efficient Road Transport. Islamic Development Bank [ongoing]	Middle East
2010	S	RETRACK–China trade routes [ongoing]	China, Far East

* Operational (O)/Tactical (T)/Strategic (S), ** online February 2020, Source: https://www.unescap.org/resources/timecost-distance-methodology (accessed on 26 February 2020).

Model Development and Policy Implications

This paper has demonstrated how an established multimodal transport model can be developed into a potential high value strategic tool to aid policymakers and planners involved in logistics and supply chain management. Analysing a variety of competing routes enables direct comparisons to be made to evaluate, for example, the quickest, shortest, cheapest or "best" route and modal mix at a given point in time. While the model was initially devised as a descriptive operations-management tool for analysing transport corridors using distance, time, cost and modal choice, a higher-level use of the would be from the perspectives of policy and strategy. At a strategic level, however, the model could aid policymakers in assessing, for example, carbon-minimising or continuous improvement strategies. Further extending the model to include forecasting and optimisation could substantially increase the usefulness of the model. This would enable commercial metrics such as inventory management or strategic stockholding algorithms to be used for both present-state analysis and for future scenario-building along the lines of "what if" modelling.

Supply chain ownership could also be incorporated into the model as this could provide clues to the competitiveness of one route against another. In this context, Schneider [58] made use of the cost model in order to carry out an internal audit; the company ships automotive components between France and South Africa, showing its value as both a theoretical operations management model and as a useful corporate costing and marketing tool. Beresford et al. [55] put the case into context, demonstrating how new business opportunities, or simply fresh theoretical solutions in the context of logistics, can emerge by using the cost model as a means to make current operations more explicit and visible.

5. Conclusions

In this research, a cost/time distance model has been identified and used as a method of analysing logistics costs, schedules and service attributes observed over a variety of routes in a wide range of operational circumstances. A number of trade-offs emerge which lie at the heart of the decision-making process within the choice of route, mode, method and carrier. It is demonstrated that a variety of transport combinations emerge as the optimum or close to optimum solutions given the overall circumstances. The model provides an excellent disciplined framework for carrying out the required analyses.

Looking more generally at global logistics management, key requirements are the delivery of the goods to the right place, at the right time and at the right price [59]. In other words, the aim is to create a supply chain, which balances cost and customer satisfaction during the transportation process within a global market. The cost of transport is the single largest element in bringing goods to market. For international movements, the search to reduce costs and improve customer service has resulted in the integration of not only the supply chain, but also activities in the supply chain, including transport, and the service providers themselves [12,60].

The model described here, developed over a period of around twenty years, not only helps to clarify the main trade-offs in a range of logistics circumstances, but also helps deepen our understanding of how the complex set of interactions have evolved over time. The model itself is not static; during the course of its development, it has advanced from being a speculative portrayal of multimodal transport chains, to a thoroughly tested and widely used operations management tool with a range of applications. At the first level, it essentially describes the progress of a freight consignment from origin to destination focusing on distance, time and cost. This framework enables like-for-like comparison of chain performance and performance variability to be quantified. However, at a second level, additional parameters such as supply chain, or segment ownership, and the interaction between 'dominant' and 'feeder' legs can be highlighted. Beyond that, a third level, such as an environmental impact measure could be grafted into the model so that commercial and environmental metrics could be visualised at the same time. In this way, the model itself can be made holistic and, as such, can help improve understanding of the structure of, and interactions within, any given supply chain.

The model as presented in this paper therefore may be used first as an analytical tool of transport operations. Second, it can inform transport and logistics operators regarding tactics for choosing, for example, least risk or maximum gain logistics solutions. Finally, the model enables policy makers to develop strategies especially in the field of international trade, which encourage growth, cooperation and development at a supra-regional level.

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