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Survey on Characteristics and Challenges of Synchromodal Transportation in Global Cold Chains

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Abstract. Transportation of perishables such as fruits and vegetables with short shelf life in international, long distance and cooled condition, plays a key role in global cold chains. Compared with truck transportation, intermodal transportation largely reduces logistics cost and emissions, however, has less flexibility for disturbances. Another aspect is that truck transportation occupies the largest share in inland transportation, which causes traffic congestion and environmental pollutions. Synchromodal transportation is a known method to study the effectiveness, efficiency and sustainability of transportation by using real-time information. However, limited articles can be found about the cold chain perspective, an integral analysis is missing. Our objective is to thoroughly analyze the characteristics and challenges of synchromodal transportation in global cold chains. The critical successful factors are analyzed at first. After that, we survey on planning problems in strategic, tactical and operational level, respectively. Finally, we conclude by suggesting further research directions.

Keywords: Global cold chains, Flexibility, Environmental impact, Synchromodal transportation, Real-time switching

1 Introduction

In this paper, we define global cold chains in perishable products with short shelf life, such as fruits and vegetables, either fresh produces or processed products. It consists of farmers, wholesalers, processors, exporters, transporters, importers, retailers and consumers [3,13,34]. As perishable products show continuous quality changes throughout the global chain, international, long distance and temperature controlled transportation is essential [4,38].

With the increasing volume of containers in global trade, intermodal transportation has been developed for integrated transport in the last decades [35]. The International Transport Forum defined intermodal transportation as: Multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of goods themselves when changing modes [14]. Compared with truck transportation, intermodal transportation can largely reduce logistics cost and emissions, however, has less flexibility for disturbances [37]. The capacity sharing of ser-

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vices among different shippers contributes to cost reduction, and the utilization of barge and train brings about less emissions. However, in global cold chains, outside temperature might vary widely during the transportation from origin to destination. In order to maintain certain temperature, flexible energy consumption is required [4]. In addition, even under optimal temperature, the quality of perishable products is still degrading with time [34,38,39]. The impact of disturbances (such as service delay and traffic congestion) for perishable products in intermodal transportation, is therefore, more critical than truck transportation. Dynamic and real-time intermodal transportation plan is needed. However, current intermodal transportation planning models tend to be static and offline, resulting in less flexibility for disturbances [6,10,11,37].

Another aspect is that truck transportation still occupies the largest share in inland transportation, which causes transportation congestion and environment pollutions. The main reason is that truck exhausts more emissions than barge and train. According to the statistics, in 2014 about 75.4% of total freight transportation in European union countries were transported via road, around 18% via rail, and 6.6% via inland waterways. The Netherlands has better performance, with 56.1%, 4.9%, and 39% respectively [15]. Recently, global cold chains are confronted with increasing consumer demands on sustainability [8,34]. Sustainability commonly refers to how the needs of the present human generation can be met without compromising the ability of future generations to meet their needs [9]. In terms of sustainable transportation, it generally relates to less emissions. Increasing the utilization of barge and train in inland transportation can reduce emissions on one side. On the other side, the transport models become more complex due to the increasing number of transfers.

Synchromodal transportation is a potential method for global cold chains to reach better performance in long distance transportation [17], first proposed by Tavasszy in 2010 [24]. It refers to creating the effective, efficient and sustainable transportation plan for all orders by using real-time information [35]. Under synchromodality, the mode combinations for orders can be changed before or during the transportation in case of disturbances. The capacity of barge and train will be better used in inland transportation for reducing logistics cost and emissions. The main objectives of synchromodal transportation focus on reducing logistics cost, emissions and improving reliability [19]. Therefore, this new transport concept has benefits on both economy, society and environment aspect. Compared with intermodal transportation, synchromodal transportation has several advantages, as shown in Figure 1. Firstly, it aims at horizontal collaboration as well as vertical collaboration. Horizontal collaboration can promote information sharing among different carriers, avoiding vicious competition. Secondly, the mode booking pattern is mode-free booking rather than mode booking in advance. The shippers only specify origin and destination position, time window, volume and lead time, leaving the choice of mode combinations to logistics service providers. Thirdly, instead of one OD pair planning, synchromodal transportation refers to network-wide planning, which includes all the orders and services arrived before planning horizon. Most importantly, it focuses on real-time switching in case of disturbances to guarantee service efficiency, operational effectiveness and less environmental impact [30,35,40].

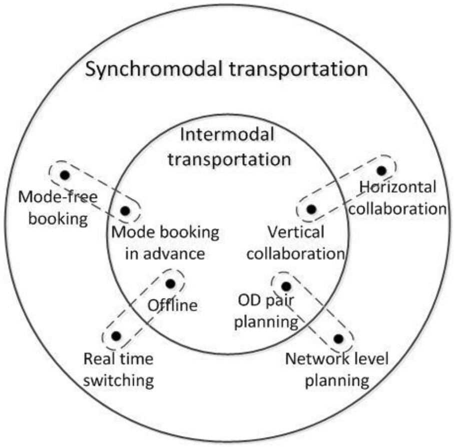

Fig. 1. Synchromodal transportation versus intermodal transportation

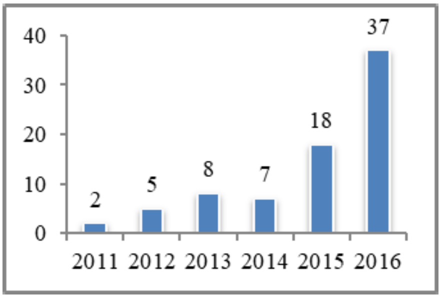

Fig. 2. Publication trends of synchromodal transportation

However, as a new concept, limited articles have been published about synchromodal transportation, especially for global cold chains. By 2016, totally 77 articles of synchromodal transportation are found using research databases, such as Web of Science, Science direct, and Emerald. Nevertheless, this research area has an increasing trend, as illustrated in Figure 2. Due to the perishability of agri-food, the transportation models are more complex than non-perishables [2,38], and only 3 papers researched synchromodal transportation involving perishable products [17,31,32]. And none of them provide an integral analysis about the characteristics and challenges of synchromodal transportation in global cold chains. The objective of this paper, is therefore, to thoroughly analyze it.

The structure of this paper is shown as follows. In Section 2, the critical successful factors are illustrated. After that, we analyze the planning problems in strategic, tactical and operational level respectively. Strategic infrastructure network design problem is described in Section 3, while Section 4 analyzes the tactical service network design problem. Operational intermodal routing choice problem is discussed in Section 5. At each level, the characteristics and challenges are discussed. We conclude our work by suggesting further research in Section 6.

2 Critical Successful Factors

Although synchromodal transportation is an interested idea, it is hard to realize in practice. Until now, only several successful pilot studies are known in the Netherlands. Almost all the case studies exist in literatures are based on the European Gateway Services network, which includes Rotterdam port and at least 20 hinterland terminals in Europe [35]. Critical successful factors analysis is an effective method to identify the key enablers of synchromodality [21]. In order to achieve an integral analysis of synchromodal transportation in global cold chains, the critical successful factors are analyzed at first.

According to the literature review, we find that synchromodal transportation includes eight factors, as shown in Table 1. Legal and political issues and physical infrastructure investment are decided by governments, such as tax incentives for sustainable logistics and new hub construction. In terms of shippers' mode booking pattern, the benefits of synchromodality, like cost receiving and environmental friendly, can promote customers' mind shift. Advanced information technology and horizontal collaboration are foundation, while service-based pricing strategy plays as an incentive. Integrated planning is the core of synchromodal transportation, which will be further discussed in strategic, tactical and operational level respectively. Real-time switching is the highest requirement which responses to dynamic demands and varying disturbances. As the first three factors are determined by government or high level organizations, next, we further analyze the last five factors.

Table 1. Critical successful factors of synchromodal transportation

Reference	Behdani (2014)	Tavasszy (2015)	Putz (2015)	Riessen (2015)	Singh (2016)	Pfoser (2016)
Legal and political issues			●		●	●
Physical infrastructure			●		●	●
Mind shift		●	●	●		●
Information technology		●	●		●	●
Horizontal collaboration	●	●	●		●	●
Service-based pricing strategy	●		●	●		●
Integrated planning	●	●	●	●	●	●
Real-time switching	●	●		●		

2.1 Information Technology

Information technology mainly refers to information sharing, track and trace, and communication technology [27]. Regarding global cold chains, radio frequency identification is a critical technology for monitoring environment data of reefer containers, such as temperature and moisture. Real-time position of services and reefer containers can be attained by using global positioning systems. Information and communications technology can promote information sharing and communication among different operators. In summary, advanced information technology is the foundation of synchromodal transportation in global cold chains.

2.2 Horizontal Collaboration

Horizontal collaboration is another basic factor in realizing synchromodal transportation. It refers to the collaboration relationship between actors in the same level, whereas vertical collaboration refers to different level. For example, the relationship among different carriers belongs to horizontal collaboration, while carriers and shippers build vertical collaboration. For switching flexibility among different services, horizontal collaboration among carriers turns out to be essential. Shippers also establish horizontal cooperation to achieve lower cost by the capacity sharing of services. The collaboration contract between them used to be long term, static and offline. However, due to the dynamic characteristic of global agri-food market, dynamic and online contract become more suitable. What is more, considering the private safety of different actors, totally information sharing is unpractical. Real-time decisions based on limited information are still challenging. Agent-based modelling is an effective method for analyzing dynamic collaboration owing to its real-time, adaptive features [12].

2.3 Pricing Strategy

In terms of pricing strategy, synchromodal transportation shows distinct characteristics with intermodal transportation [35]. Intermodal transportation adopts mode-based pricing strategy, the price is determined by the mode used. Mode combination is decided before the transportation, thus the price is fixed. With respect to synchromodal transportation, the mode booking pattern is mode-free booking. The mode combinations would be changed before or during transport in case of disturbances, such as service delay. The mode-based pricing strategy is thus unsuitable for synchromodal transportation. The pricing strategy in synchromodal transportation should be differentiate with respect to different mode combinations. Even for the identical mode combination, the price can be different according to the spare capacity of services. Considering the credits of customers, different price for different credits is an effective motivation. With regard to agri-food, received quality can further influence product's price. Based on the above analysis, we can predict that the pricing strategy of synchromodal transportation is still challenging and thus deserves further research.

2.4 Integrated Planning

An effective planning model is the core of synchromodal transportation. While intermodal transportation focus on one OD pair planning, synchromodal transportation aims at integrated planning at a network level. Under synchromodality, all the services belong to different carriers are assumed to be a large resource pool and all the arriving orders will be allocated simultaneously. Due to the complexity of planning models, most researches focus on centralized planning of synchromodal transportation. However, the entities in global cold chains are often geographically distributed. It is thus very difficult to apply a central coordinator to manage the whole system [12]. Moreover, when the computation size becomes large enough, distributed system promotes better computation performance. In order to improve operational efficiency, service effectiveness and reduce environmental impact, the key performance indicators of synchromodal transportation are logistics cost, agri-food quality and emissions. Therefore, an integrated model combining the logistics model with the agri-food quality decay model and the emission model is required for transport planning.

2.5 Real-Time Switching

With the development of information technology, real-time information becomes available for intermodal operators. Due to the occurrences of variety disturbances during transportation, such as service delay, real-time switching is essential for improving the service reliability. An integrated planning model is the prerequisite of real-time switching [36]. With respect to agri-food, the characteristics of perishable and short shelf life also requires real-time switching in case of disturbances [17]. Otherwise, the quality may decay to an unacceptable level for customers. In order to realize real-time switching, researchers have proposed different methods, like rolling horizon strategy, model predictive control, decision tree and decomposition algorithm. In rolling horizon strategy [1], orders arrive continuously in different planning horizons. The planning horizon is rolled forward to include more known information. Decisions are made at the deadline of the orders. Regarding model predictive control approach [17], it is an effective method to obtain an ideal output by controlling the inputs. For instance, in order to keep banana's shelf life, both the container's temperature and mode choice will be controlled by the system operators in real-time. As for decision tree [36], it can be used in a decision support system for instantaneously allocating incoming orders to suitable services, without the requirement of continuous planning updates. Decomposition algorithm attempts to solve the original problem by solving a number of smaller problems [18]. As real-time switching requires short response of disturbances, the computation efficiency indicates significant means.

2.6 Discussion

According to the discussions above, we know that under government support, based on advanced information technology and horizontal collaboration as well as attracted pricing strategy, the synchromodal transportation can be realized in global cold chains by combining real-time switching with effective planning models. However, synchromodal transportation planning models are more complex than intermodal transportation. Considering the perishability of agri-food, both the objectives and constraints will be different. Next, we will further analyze the characteristics and challenges of synchromodal transportation in global cold chains in strategic, tactical and operational level respectively.

3 Strategic Infrastructure Network Design

Strategic level focuses on long term decisions. The infrastructure network design problem in synchromodal transportation refers to investment decisions on hub locations [6,29]. Under synchromodal transportation, different shippers' containers are bundled together in hubs for large container flow. To reduce total transport cost, the allocation of hubs depends on the service demands in different areas. The connection between hubs can be road, rail or inland waterway. Under the same OD pair, different corridors refers to different modes. Regarding global cold chains, due to the short shelf life and low temperature requirements of perishable products, the location of processing factory is also an important strategic decision. Considering the logistics performance of global cold chains, different locations of processing factory will result in different transport mode combinations choice. For example, the pineapples from Ghana to the Netherlands can be cutting in Ghana and then transport to the Netherlands by aircraft, or transport to the Netherlands by barge at first and then cutting in the Netherlands, as shown in Figure 3 [34].

The infrastructure network design problem mainly depends on the availability of infrastructure, transport assets, the adequacy of cargo flow in a specific corridor and the shelf life of perishable agri-food [6,34]. Typically, this problem can be described by using mixed-integer linear programming models which include both binary decision variables and continuous decision variables. Binary decision variables is related to that whether the hub or processing factory is used or not, while continuous decision variables illustrate bundled flow [4].

The objective of the network design used to be simply focus on cost. As agri-food quality deeply affects customers satisfaction degree, it should be considered as another important objective. With respect to environmental impact, proper network design maximizes the utilization of green modes which produce less emissions. Thus, for global cold chains, the objectives of infrastructure network design should include both logistics cost, products' quality and emissions.

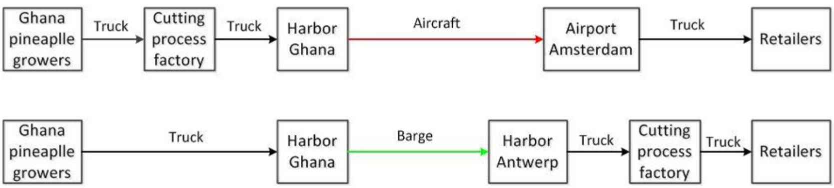

Fig. 3. Transportation of Pineapples from Ghana to the Netherlands

4 Tactical Service Network Design

Tactical level focuses on middle term decisions. It optimally utilizes the given infrastructure by choosing services and associated transportation modes, allocating their capacities to orders, and planning their itineraries and frequency. Service network design (SND) is the major problem in tactical level. It mainly gives decisions on choosing the transportation services and modes for forecasted customer demands, and the frequency and capacity of each mode on certain corridor [29]. Here, a service is characterized by its origin, destination and intermediate terminals, its transportation mode, route and its service capacity. Likewise, a mode is characterized by its loading capacity, speed and price [29], which means that different services may have a same mode. As synchromodal transportation aims at integrated planning, both self-operated or outsourced transportation need to be considered to minimize transport cost [25].

In order to improve operational efficiency, service effectiveness and sustainability, the objectives of SND problem of synchromodal transportation for perishables include logistics cost, products quality and emissions. The availability and capacity of infrastructure networks or inland terminals are the primary resource constraints [6]. In intermodal transport planning, dynamic service network design problem is closest to the synchromodal planning problems. It involves the selection of transportation services and modes for freights, where at least one feature of the network varies over time [26]. Except time-varying network, the demands of synchromodal transportation is also dynamic. Orders arrive in sequence rather than in advance before the planning horizon. According to the perishable and dynamic characteristics of global cold chains, we analyze the challenges exist in six aspects of SND problem given in Table 2.

Table 2. Service network design problem

Reference	Riessen et al. (2015)	Rivera et al. (2016)	Li et al. (2016)
Mode	Rail, Truck, Barge	Rail, Truck, Barge	Rail, Truck, Barge
Objectives	Cost	Cost	Cost
Centralised /Distributed	Centralised	Centralised	Distributed
Transfer cost	Yes	No	Yes
Self-operation/ Outsource	Both	Self-operation	Both
Static/Dynamic	Static	Dynamic	Dynamic

4.1 Distinct aspects

For global cold chain, transportation distance tends to be very long. As agri-food is distinct from other products, temperature controlled transportation is essential. Compared with sea transport, rail transport is more faster than sea transport. Compared with air transport, the cost of rail transport is 50% less than air transport. This means that the rail transport is optimally suited for perishable products which need to be at the final destination as quick as possible, but not at any cost. However, for perishable products with high value and short lead time, air transport is a better choice. Both Riessen [25], Rivera [26] and Li [16] only consider mode combinations of truck, barge and train.

As agri-food is perishable and reefer containers exhaust extra emissions, the objectives of transportation should include the reduction of cost, emissions, and improving service reliability. Both Riessen [25], Rivera [26] and Li [16] only view cost as objective.

Compared with centralized planning systems, decentralized systems are more practical. Farms, processing factories and retail stores tend to be generically distributed. Information sharing is crucial for centralized planning. However, it is difficult to realize among different entities, especially for stakeholders with competitive relationship. Li [16] proposed a distributed service network design approach, however, this approach is applied in general supply chain.

4.2 General aspects

Transfers brings more chance to the utilization of barge and train, which result in less emissions and cost. However, it also takes additional cost and time in terminals. Thus, transfer cost should be calculated in transport cost, like Riessen [25] and Li [16].

Outsourced logistics refers to horizontal collaboration between different carriers. Self-operated logistics is calculated on fixed cost. In contrast, outsourced logistics is based on container volumes. In terms of service capacity, the capacity of self-operated logistics can be completely used, while the capacity of outsourced logistics depends on spare capacity [25].

SND problem can be further divided in static and dynamic groups [29]. Riessen [25] proposed a static SND model, temperature and travel time are assumed as static parameters, and all the orders arrived before the planning horizon. However, time-varying network is more practical, because transport conditions normally change with time, and orders tends to be arriving in sequence. In addition, Li [16] proposed a dynamic SND model in synchromodal transportation based on a model predictive control approach.

4.3 Discussion

Synchromodal transportation service network design problem in global cold chains is a challenging problem owing to its dynamic, long distance, multi-objective and distributed features. To our best knowledge, only Riessen [25], Rivera [26] and Li [16] proposed SND model for synchromodal transportation. But none of them considered the characteristics of global cold chain. Therefore, there still have lots of chances for further research of dynamic SND problem for global cold chains.

5 Operational Intermodal Routing Choice Problem

Operational level deals with dynamical problems that are not explicitly addressed at strategic and tactical levels [29]. In the operational level, the mainly issue is the determination of the best choice of services and the associated transportation modes, best itineraries and allocation of resources to demands [29]. Nevertheless, the intermodal routing choice decision is designed for orders in this level, while for services in tactical level. The demand is the actual demand rather than the forecasted demand, and the resource constraints are the time windows rather than availability and capacity of infrastructure and services. Within the constraints of tactical service design (which determines the routes, frequency, and capacity of each modality), the operational level considers the details of transport orders and resources, then the orders to different intermodal transport services are assigned.

The operational intermodal routing choice (OIRC) problem refers to the selection of mode combinations for arriving orders. Based on different characteristics, researchers proposed different titles for the OIRC problem, such as international intermodal choices [20], intermodal route selection [28], international intermodal routing [5,10], intermodal freight routing problem [11], container transportation planning problem [37], operational service schedules [6], and selection of transport mode combination [19]. Although this problem has been investigated so many years, limited publications can be found in literatures. The mainly reasons are the complexity of computation, and the dynamic feature of both demand and supply. Other reasons include the unattainable of information, the competition relationship instead of cooperation relationship among operators.

Compared with intermodal transportation, the operational intermodal routing choice problem in synchromodal transportation has several new characteristics. Firstly, the routing choice decisions are made at network level and in real-time. Secondly, the inland transportation modes are mainly barge and train. Truck is only used for the first and last mile transportation or for urgent demands.

For global cold chain, operation routing choice problem faces several new challenges. According to the perishable and dynamic characteristics of global cold chains, we analyze the challenges exist in eight aspects of operational intermodal routing choice problem, as shown in Table 3.

Table 3. Operational intermodal routing choice problem

Reference	International/ Inland	Multi-objective	Time window	Time-varying network	Centralized/ Distributed	Multi-pattern	Transfer	Real-time/ Dynamic
Mes (2016)	Inland	Cost, Time, Emis-sions	Yes	No	Centralized	No	Yes	Real-time, Dynamic
Riessen (2016)	Inland	Cost	Yes	No	Centralized	Yes	Yes	Real-time, Dynamic
Riessen (2015)	Inland	Cost	Yes	No	Centralized	Yes	Yes	Offline, Static
Behdani (2014)	Inland	Cost, Time	Yes	No	Centralized	No	No	Offline, Static
Cho (2012)	International	Cost, Time	No	No	Centralized	No	Yes	Offline, Static
Chang (2008)	International	Cost, Time	Yes	No	Centralized	Yes	Yes	Offline, Static
Ziliaskopoulos (2000)	-	Time	No	Yes	Centralized	No	Yes	Offline, Static
Bookbind-er (1998)	International	Cost, Time	No	No	Centralized	No	Yes	Offline, Static
Barnhart (1993)	National	Cost	No	No	Centralized	Yes	Yes	Offline, Static
Min (1991)	International	Cost, Time, Risk	No	No	Centralized	No	Yes	Offline Static

5.1 Distinct aspects

Typically, global transportation can be divided into international and national/inland transport [35]. The literatures that researched on international transportation normally regard truck as the only transport mode in inland transportation [7,10,11,20]. With the development of hinterland terminal, researchers begin to focus on the combinations of truck, train and barge in inland transportation [6,19,37].

Due to the perishable and dynamic characteristics of agri-food, the objectives of OIRC problem consists of reducing logistics cost, preserving product quality and reducing emissions. This problem thus belongs to multi-objective planning problem. Multi-objective planning is more complex than single objective planning. One method is to assign different weights for different objectives, and then summarizes these objectives as a single objective [10]. Another method is to solve all the single objective respectively while others are assigned as constrains. Pareto optimum solutions can be attained by optimisation and composition method[11].

Time constraints can be described either implicitly or explicitly. Time window [6] explicitly represents time constrains, while total transport time limitation [7] is implicitly. The time windows of terminals, services and orders both have important influences on route decision. For agri-food, total transport time limitation is critical because of the perishable characteristic.

Time-varying network has developed fast recently. Transport cost, transport time and environment temperature normally change with time [41]. Time expanded network is an extended graph based on time and space information. Under time expanded network, the shortest path with time windows is easy to find [18].

According to Table 3, we can find that both of these literatures proposed centralized model. As computation size increases, distributed model promotes better performance than centralized model [12,16]. Furthermore, the stakeholders of global cold chain tends be to distributed worldwide, distributed model is more practical.

5.2 General aspects

As for the multi-pattern aspect, it refers to the demand patterns of customer. Different patterns correspond to different information about origination, destination, container volume and time windows. Only Riessen [37], Chang [10] and Barnhart [5] considered multiple demand patterns in the intermodal routing choice model.

With the increasing of transfer number, the OIRC model becomes NP-hard problem [19]. An effective algorithm is significant for computational efficiency. Researchers proposed different algorithms recently, like decision tree [36], k-shortest algorithm [19], rolling horizon [18] and decomposition algorithm [10].

Typically, intermodal routing choice problem is static and offline [5,7,10,11,20]. The planning horizon used to be one day. The intermodal planning system assume all the information of shippers and carriers are accessed before the planning horizon [5]. However, in practice, it is difficult to achieve or predict all the information before planning [6]. Thus, dynamic/real-time routing choice is critical in synchromodal transportation [36].

5.3 Discussion

Based on above analysis, we conclude that OIRC problem for global cold chains is still challenging. To our best knowledge, none of these literatures consider both the aspects of dynamic/real-time, distributed/peer-to peer, transfer and time-varying network. What's more, none of them consider the characteristics of global cold chain. As OIRC problem in synchormodal transportation is NP-hard problem, only sub-optimal algorithm can obtained by using heuristic algorithms. As a result, how to improve the computation efficiency and effectiveness simultaneously deserve further research.

6 Conclusion

Temperature controlled transportation of perishables plays a key role in global cold chains. Synchromodal transportation is an effective method, which characterized by flexibility, reliability and sustainability. However, limited articles have published about the cold chain perspective, an integral analysis is missing.

In order to analyze the characteristic and challenges of synchromodal transportation in global cold chains, we have discussed the critical successful factors at first. We found that information technology and horizontal collaboration are the foundation factors, while service-based pricing strategy plays as an incentive. Integrated planning model is essential, and real-time switching is the most challenging factor.

After that, we have further discussed the planning problems in three different levels. Strategic infrastructure network design problem refers to hub location and processing factories location. Tactical service network design problem decides mode routes and the frequency of services. Operational intermodal routing choice problem aims at real-time matching different orders with different mode combinations. While infrastructure network design problem and service network design problem focus on infrastructures and services, respectively, operation intermodal routing choice problem researches on the decision of orders.

In our future work, we will focus on the operational intermodal routing choice problem under synchromodality. We call it mode matching problem in our project. First, we will research on dynamic/real-time mode matching problem. Rolling horizon framework and decision tree are potential tools. Second, the multi-hop transfer will be considered to improve matching rate. Since the problem is NP-hard problem, heuristics algorithm will be used. After that, we prefer to focus on distributed/peer-to-peer mode matching. Agent-based modelling tends to be an effective method. Finally, considering the practical factors, time-vary travel time and temperature deserve further research. Time-expanded network will be used based on time, temperature and location information.

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