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Toward sustainable port-hinterland transportation: A holistic approach to design modal shift policy mixes

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ABSTRACT

Port-hinterland transport involves freight gathering and distribution between hinterland economies and ports. It is responsible for a major portion of the negative externalities of the entire port-related logistic chain. This study proposes an integrated model framework to facilitate the design of modal shift policy mixes to increase the sustainable performance of port-hinterland transport. The integrated model framework consists of three parts: (1) an econometric model to transform the hinterland economic scenarios into changes in port throughput, (2) a system dynamic model to estimate the changes in port-hinterland freight externalities due to changes in port throughput, and (3) a Monte Carlo simulation to identify those modal shift policy mixes with lower freight externalities. The proposed methodology is applied to Qingdao Port and its hinterland freight transport in China. The results show that hinterland economic growth will significantly raise port throughput and port-hinterland transport externalities. Four common modal shift policy instruments are considered, namely, internalization of external cost (IEC)-based pricing, road construction, increasing railway service level, and railway subsidy. The results show that the policy mix's efficacy in reducing externalities increases with the increase in freight demand, but the holistic effect of the policy mix is lower than the sum of the effects of individual policies because these policies share the goal of facilitating modal shifts. The results of Monte Carlo simulations show that despite the uncertainty for hinterland economic prospects, the policy mixes with better performance in reducing externalities commonly include IEC-based pricing and increasing railway service level. The proposed methodology provides decision makers with a systematic framework for policy making toward sustainable port-hinterland transport.

1. Introduction

Freight transport faces challenges in achieving sustainability because it is intertwined with economic growth. This situation is particularly evident for ports, which are considered one of the most prosperous economic centers by connecting cross-sea shipping and hinterland transport (Gonzalez Aregall et al., 2018). Within the entire port-related logistic chain, port-hinterland transport, which

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accounts for freight gathering and distribution (Talley and Ng, 2017, 2018), is responsible for a major portion of the negative externalities (primarily including greenhouse gas (GHG) and air pollutant emissions, congestion, and traffic accidents). In a multimodal port-hinterland freight system, coordinating road and railway transport is important for sustainability (Liu et al., 2021). However, roads still play dominant roles in most port-hinterland transport systems despite their low environmental performance. This issue is particularly evident for China. Sea-rail freight accounts for only 2.6% of the total container throughput of coastal ports (Editorial Board of China Ports Yearbook, 2020). Thus, promoting a modal shift via targeted policies is important for port-hinterland transport systems to achieve sustainability.

There are multiple ways to facilitate freight modal shifts, for example, the internalization of external cost (IEC)-based pricing to reverse the competitive condition of roads and railways (Dente and Tavasszy, 2018; Iannone, 2012); tax or subsidy incentives to increase shippers' preferences for railway transport (Li and Zhang, 2020; Liu et al., 2010); and road and railway infrastructure construction to reduce road congestion and increase railway service levels (Liu et al., 2021). Furthermore, these modal shift measures are commonly implemented simultaneously to develop the form of the policy mix (Bouma et al., 2018). Since the concept of policy mix was proposed by Nobel Prize winner Robert A. Mundell (Mundell, 1962), it has been extensively investigated in the fields of macroeconomy and technology innovation (Bianchi and Ilut, 2017; Söderholm et al., 2019). The form of the policy mix in the field of port-hinterland transport and its impact on reducing transport externalities deserve dedicated investigation.

Assessing the impact of the modal shift policy mix on port-hinterland transport is a complex issue. This complexity originates not only from the intertwined port-hinterland transport processes, such as freight flow, traffic flow, and mode choices, but also from the interconnection between ports and the economy of hinterlands (Liu et al., 2019). In academia, most existing studies focus on either the economic or the environmental performance of port-hinterland transport. However, few studies have incorporated the impact of hinterland economic transitions into modal shift decision making, and the optimized design of modal shift policy mixes based on their holistic impacts on port-hinterland transport sustainability has not been investigated.

This study makes two main contributions. First, this study addresses the economy of hinterland and port-hinterland transport in an integrated manner. An integrated model framework that combines econometric and system dynamic approaches is proposed to explore the holistic impact of both structural transition in the hinterland economy and the modal shift policy mix on the sustainability of port-hinterland transport. Interactions among multiple policy instruments and their impact on port-hinterland freight processes and sustainability are investigated. Second, this study facilitates the design of modal shift policy mixes to increase port-hinterland sustainability under the uncertainty of hinterland economic prospects. Based on the proposed model framework, Monte Carlo simulations were introduced not only to address the uncertainty of both policies and hinterland economic prospects but also to determine which policy mixes lead to better sustainable performance. The proposed methodology provides decision makers with a systematic framework for policy making toward sustainable port-hinterland transport.

The remainder of this paper is structured as follows. Section 2 presents a literature review. Section 3 elaborates the proposed methodology, including the overall analytical flow, constituent models, and the implementation of the integrated model framework. Section 4 demonstrates the proposed methodology by applying it to the port-hinterland transport system of Qingdao Port, China. Section 5 shows the impact of modal shift policy mixes on the sustainability of this system. Section 6 proposes optimized modal shift policy mixes to increase sustainability. Section 7 summarizes the conclusions and suggests directions for future work.

2. Literature review

2.1. *Sustainable port-hinterland transport*

According to the review of Gonzalez Aregall et al. (2018), among the 365 ports around the world, only 76 ports have taken measures to address the negative externalities of port-hinterland transport systems. Within the entire port-logistic chain, port and shipping were the focus of previous studies (Bergqvist and Egels-Zandén, 2012). Later, the environmental performance of port-hinterland transport attracted increasing attention from academia (Sdoukopoulos and Boile, 2020). Bergqvist et al. (2015) scrutinized alternatives for port-hinterland transport development and found that sustainable port-hinterland transport strategies have not been fully explored. This would entail a full understanding of freight transport systems, whose environmental performances are related to freight volume, infrastructure, vehicle fleets, energy sources, and policies. For example, Dente and Tavasszy (2018) and Tavasszy et al. (2011) investigated changes in freight volume and traffic flow due to economic or policy changes; Huo and Wang (2012) simulated the dynamics of vehicle sales and stock and the penetration of heavy vehicle powertrain technology; Sathaye et al. (2010) and Wang et al. (2020) explored the impact of investment on road network capacity; and Atmanlı et al. (2014) and Cai et al. (2012) investigated the impacts of fossil fuel substitution, emission standards, and fuel tax on the environmental performance of freight transport.

Port-hinterland transport is differentiated from general freight systems by its connection with ports, which are a strategic endowment that connects global and local markets (Bottasso et al., 2014). Previous studies have revealed interrelationships between ports and the economy of the hinterland (Deng et al., 2013; Shan et al., 2014; Yang et al., 2019). For example, Rashed et al. (2018) examined the relationship between economic activity in the hinterland and port freight demand. On this basis, they projected the container throughput of the Hamburg-Le Havre range of ports and scheduled port capacity-building planning. Shan et al. (2014) found that trade facilitation of good harbors is important to promote regional economic development. Nonetheless, existing studies have not extended the impact of the hinterland economy to port-hinterland transport. The issue of how to achieve sustainable port-hinterland transport under the uncertainty of hinterland economic transitions has yet to be solved. As Sdoukopoulos and Boile (2020) suggested, rapidly evolving business trends and market developments entail the adoption of a more holistic perspective for analyzing port-hinterlands.

2.2. Modal shift policy mix for sustainable transport

Transport sustainability can be quantified in terms of transport external costs, which primarily include costs related to global warming, air pollution, accidents, and traffic congestion (Demir et al., 2015). One of the most common measures to reduce transport-related negative impacts is to promote modal shift. The European Union takes modal shift as the focus in its transportation decarbonization strategies; for example, the port of Rotterdam plans to break away from road dependence by 2035 (Kaack et al., 2018). Existing studies have demonstrated the impact of modal shift strategies on transport sustainability. Dente and Tavasszy (2018) conducted an empirical analysis of interregional trade activities in France. They found that the IEC mechanism promoted modal shift and reduced the adverse impact of freight transport on the environment. Santos et al. (2015) suggested direct subsidies for railway shippers, which have the potential to increase railroad intermodal freight competitiveness. Li and Zhang (2020) proposed deregulation of railway pricing to improve its competitiveness.

Existing studies have investigated the effects of individual policy instruments. However, policy interventions toward sustainability tend to be multidimensional and interactive; this complicates policy assessment and design in the form of a policy mix, which was proposed early in the macroeconomy (Mundell, 1962). Policy mix refers to the combination of multiple policy instruments due to their simultaneous implementation (Cunningham et al., 2013). Bouma et al. (2018) emphasized mutual reinforcement or trade-offs among alternative policy instruments in a policy mix. In view of this feature, there remains a lack of knowledge on the holistic impact of the modal shift policy mix on the sustainability of port-hinterland transport.

2.3. Research gap

Within the entire port-related logistic chain, the sustainable performance of port-hinterland transport and the impact of modal shift policy mixes deserve dedicated investigation. Port-hinterland freight types and amounts are influenced by the economy of the hinterland. To date, the impact of the hinterland economic transition on port-hinterland transport remains unexplored, and the holistic effect of the modal shift policy mix on the sustainability of port-hinterland transport lacks in-depth analysis. To fill these research gaps, this study develops a holistic approach. This approach combines econometrics, system dynamics and Monte Carlo simulations to address the hinterland economy and port-hinterland transport in an integrated manner. On this basis, it facilitates the design of modal shift policy mixes to increase the sustainability of port-hinterland transport.

3. Methodology

3.1. Overall analytical flow

General port-hinterland transport systems can be abstracted as a hub-and-spoke manner (as illustrated in Fig. 1) (Woxenius, 1997), with multimodal or intermodal transport from port to hinterland terminals and vice versa (De Langen et al., 2013). The sustainable performance of port-hinterland transport is influenced by both the economy of the hinterland (which correlates port throughput and port-hinterland freight demand) and policy mixes (which promote modal shift).

To quantify the holistic impact of the hinterland economy and modal shift policy mix on the sustainability of port-hinterland

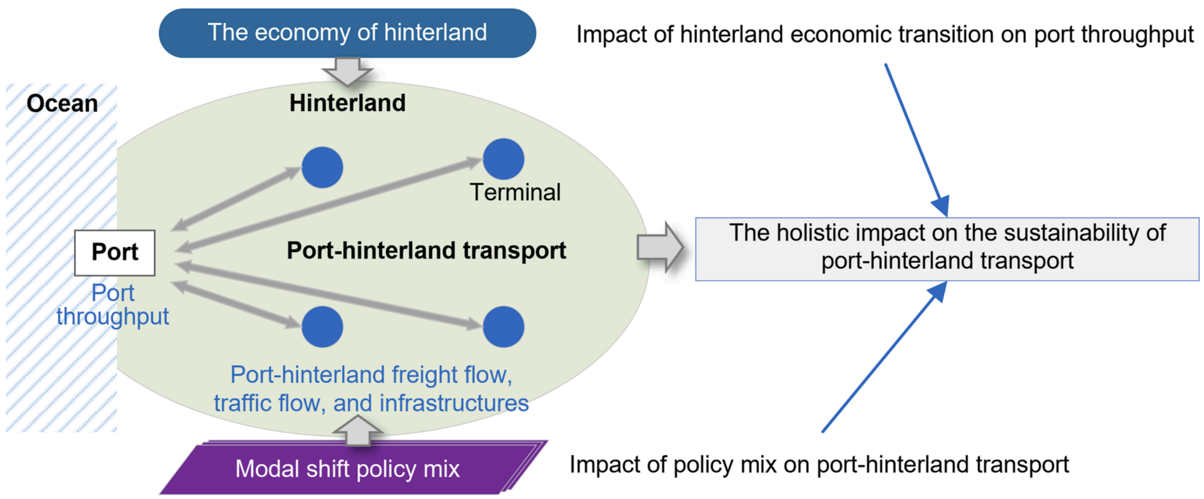

Fig. 1. Illustration of the holistic impact of both structural transition in the hinterland economy and the modal shift policy mix on the sustainability of port-hinterland transport.

transport, the proposed analytical flow consists of three sequential parts, scenario setting, model establishment, and model simulation, as illustrated in Fig. 2. First, economic scenarios are defined to reflect different economic prospects. Next, an integrated model framework is established. The framework employs an econometric model to transform the hinterland economic scenarios into changes in port throughput, followed by a port-hinterland transport model to estimate the changes in port-hinterland freight externalities due to changes in port throughput. By coupling these two models, the holistic impact of both the structural transition in the hinterland economy and the modal shift policy mix on port-hinterland transport is captured. Finally, using the system dynamic model to perform Monte Carlo simulations, modal shift policy mixes to increase the sustainability of port-hinterland transport are formulated.

3.2. *The integrated model framework*

The integrated model framework is developed based on the classic four-step transport theory, which divides freight processes into four steps: freight generation, trip distribution, modal split, and traffic assignment (De Jong et al., 2012; Tavasszy and De Jong, 2013). Accordingly, the integrated model framework consists of the following interrelated submodels. First, port throughput under different economic scenarios is estimated in the *port throughput estimation submodel*, acting as aggregate freight demand. Next, freight demand is divided into different transport modes in the *modal split of the port throughput submodel*, and freight traffic is simulated on the aggregate level by the *port-hinterland traffic submodel*. Externalities (in the form of external costs) incurred by freight traffic are estimated in the *port-hinterland sustainability submodel*. Finally, the modal shift policy mix is included via multiple submodels, as illustrated in Fig. 3.

3.2.1. *Port throughput estimation submodel*

An econometric model is introduced to correlate port throughput and the economy in the hinterland. Economic indicators including (but not limited to) the total value of imports and exports and gross industrial product are used to explain the change in port throughput, while multimodal transport mileages are used as control variables because infrastructure represents the great potential of trade access (Hui et al., 2010; Rashed et al., 2018). Thus, a general econometric model that explains the change in port throughput is expressed as Eq. (1):

$$PT_t = a_0 + \sum_i \beta_i e_{it} + \sum_i \alpha_i c_{it} + \varepsilon_t \tag{1}$$

where e_{it} and c_{it} are explanatory variables and control variables, respectively, and ε is a disturbance term.

3.2.2. *Modal split of the port throughput submodel*

On the land side of ports, freight is handled by a multimodal port-hinterland transport system, which commonly includes road, railway, and inland waterway transport. Normally, railways and inland waterways have an advantage in freight rates, but their flexibility and accessibility are commonly lower than those of roads. These characteristics are summarized in terms of generalized cost (Sharon et al., 2017), based on which mode shares can be estimated. On the other hand, modal shift policy instruments influence the competitive condition among roads, railways, and inland waterways. To apportion freight demand, a logit model is employed (Kurtuluş and Çetin, 2020), as specified in Eq. (2):

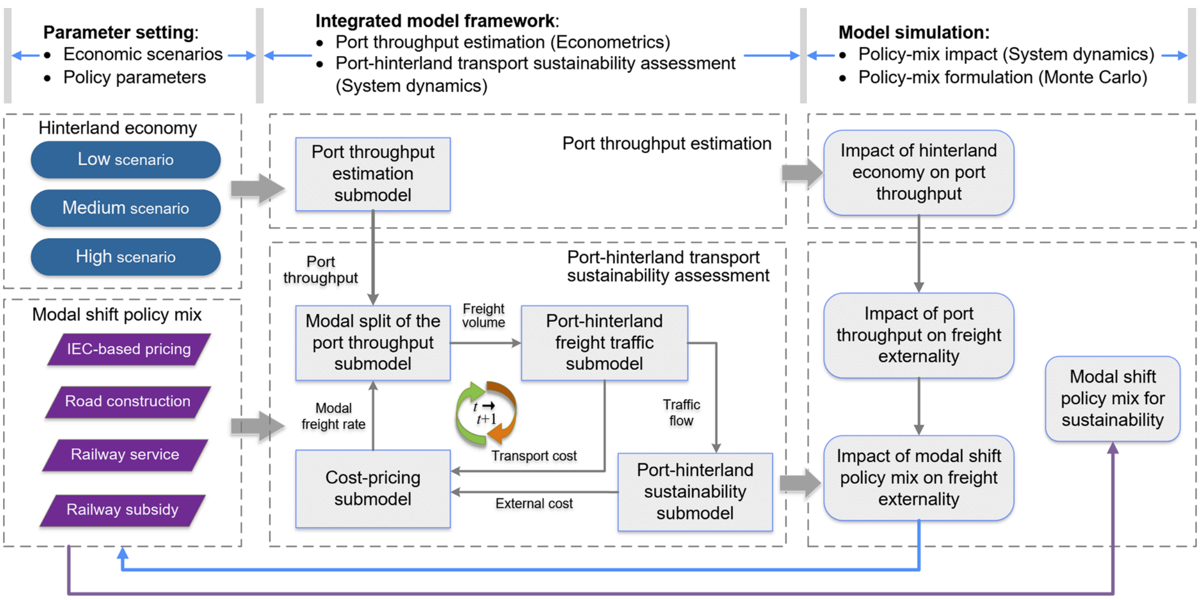

Fig. 2. Schematic illustration of the overall analytical flow.

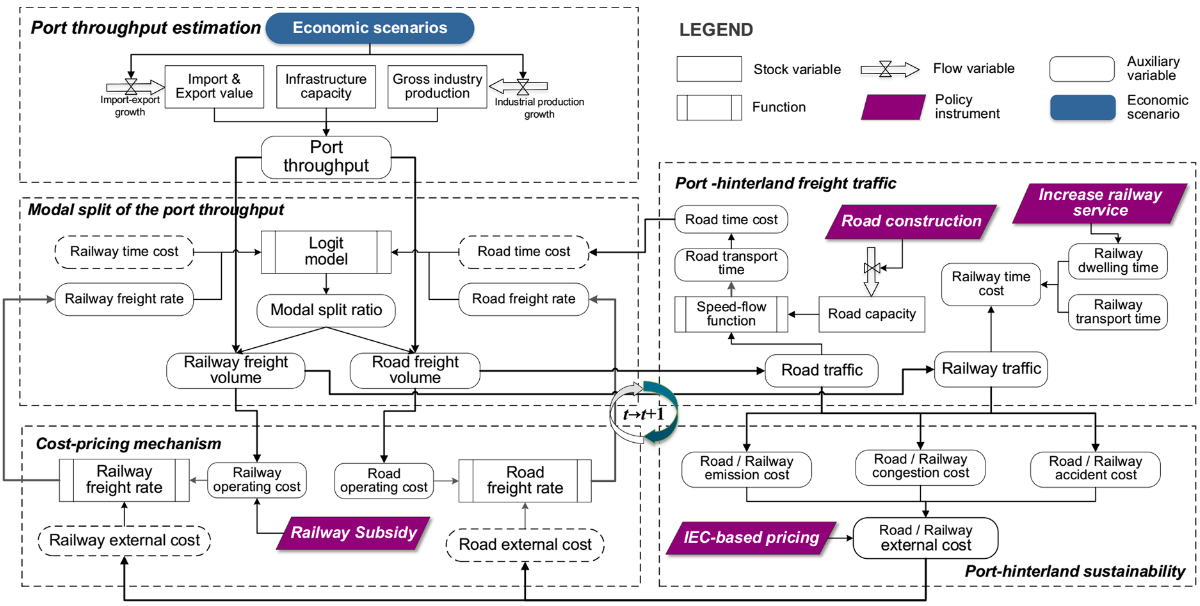

Fig. 3. Schematic illustration of the integrated model framework and the systematic intervention of the modal shift policy mix.

$$\begin{cases} f_t^k = PT_t \times r_t^k \\ r_t^k = \dfrac{\exp(\alpha \times g_{t-1}^k)}{\sum\limits_{k \in \mathbf{K}} \exp(\alpha \times g_{t-1}^k)} \end{cases} \tag{2}$$

where k belongs to the transport mode vector $\mathbf{K} = (\mathrm{RD}, \mathrm{RW}, \mathrm{IW})$, which includes roads, railways, and inland waterways. f_t^k is the freight demand for mode k, which is derived by splitting the total freight demand (namely, port throughput PT_t in Eq. (1)) according to the mode share r_t^k. Particularly for railways in China, freight volume cannot exceed the regulated capacity of infrastructure. Thus, for railway transport, $f_t^{RW} = \min(PT_t \times r_t^{RW}, q_t^{RW})$, where q_t^{RW} denotes railway capacity. r_t^k is determined by the generalized cost g_t^k, which includes the time cost and the freight currency cost (Tavasszy and De Jong, 2013). Both costs are related to freight traffic flows and are estimated through the following two submodels.

3.2.3. *Port-hinterland traffic submodel*

This submodel converts freight flows into traffic flows and estimates the freight generalized cost. Particularly for road transport, congested roads lead to greater time delays (Li et al., 2020). These effects are reflected in the generalized transport cost g_t^k, as expressed in Eq. (3).

$$\begin{cases} g_t^k = p_t^k + VOT_t^k \times T_t^k \\ T_t^{RD} = \dfrac{1 + e^{\omega_t \ln(v_t/q_t)}}{\lambda \times S_t} \\ \omega_t = \mu + \gamma \times (v_t/q_t)^3 \end{cases} \tag{3}$$

where g_t^k consists of freight time cost $VOT_t^k \times T_t^k$ and freight currency cost p_t^k, which is affected by the pricing-related policy addressed in the following *cost-pricing submodel*. VOT_t^k represents the value of time, which is related to cargo types. T_t^k is the transport time. Particularly, railway and inland waterway transport time includes the significant waiting time at terminals, and road transport time considers the congestion effect, which is quantified by the speed-flow function using both the volume of traffic flow (v_t) and road capacity (q_t) (Einbeck and Tutz, 2006). v_t is derived by both the freight flow (f_t) and the average trip distance (l^k), as expressed in Eq. (4).

$$v_t = f_t^k \times l^k \tag{4}$$

Since the model works on the aggregate level, the average trip distance (l^k) is obtained by the economically weighted approach based on both the freight volumes between port and hinterland terminals and their corresponding transport distances (Gutiérrez et al., 1996; Liu et al., 2015).

Via Eq. (3), infrastructure-related policies are incorporated. Road construction increases road capacity (q_t) and reduces road transport time T_t^{RD}. Railway construction or collaboration between ports and railway carriers can increase the railway service level and reduce the railway transport time T_t^{RW}.

3.2.4. Cost-pricing submodel

In the freight market, shippers' freight currency cost p_t^k depends on the freight rate (price) provided by carriers. This submodel simulates the freight cost-pricing mechanism and incorporates pricing-related policies. The freight rate is determined by multiple factors, such as operation costs during transport and terminal handling, government taxation, and supply and demand conditions of hinterland transport (Li and Zhang, 2020), while pricing-related policies change the pattern of freight costs and affect freight rates (Welch and Mishra, 2014). This mechanism is expressed as follows.

First, freight operation cost $O(F_t, V_t^k)$ is structured as Eq. (5):

$$O(F_t, V_t^k) = \sum_m F_t^m \times H_t + \sum_n V^n \times f_t^k + MA \tag{5}$$

where **F** and **V** represent the unit fixed and variable costs, respectively, which include *m* and *n* cost items based on the cost structure proposed by Bösch et al. (2018). **H** represents vehicle stock, which is simulated by a vehicle scrap-sale model (Huo and Wang, 2012; Liu et al., 2019). *MA* denotes the management cost, which is assumed to be constant.

Next, the freight rate is estimated considering both the freight operation cost and the supply–demand relationship of hinterland transport. The principle of profit maximization is introduced to represent the relationship among freight carriers' profit, revenue, and cost, as specified as follows.

$$Max : PROFIT_t = R(p_t, f_t^k) \times (1 - r) - O(F_t, V_t^k) + S(f_t^k) \tag{6}$$

where *R*, *O*, and *S* denote freight carriers' revenue, operation cost, and subsidy, respectively, and *r* is the tax rate. In addition, the price elasticity (e_D) is introduced to reflect the effect of the supply–demand condition of hinterland transport. Therefore, the freight rate (p_t) is obtained in Eq. (7) (detailed solution process is available in Appendix A1).

$$p_t = \frac{O(F_t, V_t^k) - S(f_t^k)}{2 \times f_t^k \times (1 - r)} + \frac{p_{t-1}}{2} - \frac{p_{t-1}}{2 \times e_D} \tag{7}$$

Fiscal or pricing policies are incorporated via Eq. (7). IEC-based pricing changes freight rate p_t by imposing an additional externality-related cost on freight operation cost $O(F_t, V_t^k)$. A railway subsidy is introduced via $S(f_t^k)$, which reduces the railway freight rate. These policies change freight rate p_t in Eq. (7) directly, which further influences the transport generalized cost g_t^k in Eq. (3) and mode share r_t^k in Eq. (2).

3.2.5. Port-hinterland sustainability submodel

In this submodel, port-hinterland sustainability is assessed in terms of external costs. Four common negative externalities of transport are considered: GHG emissions, air pollutant emissions, congestion, and traffic accidents. Since the model functions at the aggregate level, these externalities are estimated according to traffic volume and average incidences. All these externalities are converted into dimension-consistent monetary external costs, as specified as follows.

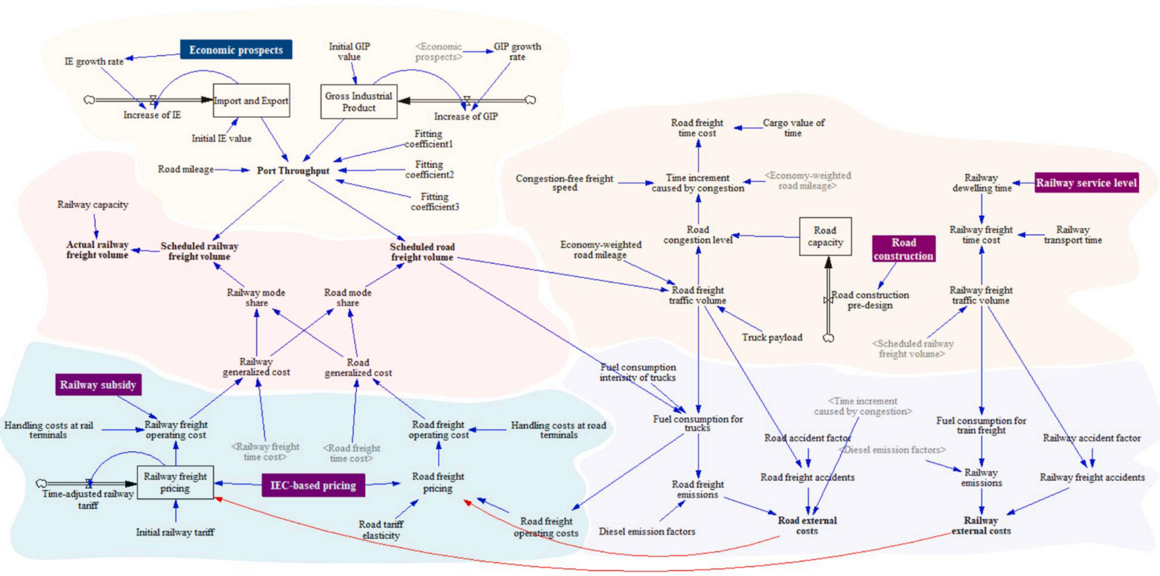

Fig. 4. The implemented model framework in the Vensim DSS® software package.

1. Emission cost (EC). Since most current freight vehicles consume fossil fuels, freight emissions occur along with freight traffic flow. Transport-related GHG and air pollutant (commonly including CO, NO_x, HC, and PM) emissions are estimated based on the fuel/energy consumption of freight traffic flow (v_t in the *port-hinterland traffic submodel*) and emission factors (EFs) (whose values refer to Peng et al. (2015)). Improvement in fuel/energy efficiency is also considered (Liu et al., 2015). On this basis, the emission cost is obtained via the monetized values of emissions (Yang, 2013).

2. Congestion cost (CC). Freight traffic may cause congestion and additional transport time. Congestion occurs more frequently within port-hosted cities and less frequently on highways outside cities. This study considers this condition via the differences in both road capacity and road lateral interference coefficient (more lateral interferences within cities). Congestion cost is obtained according to the marginal time-added value ($\partial T_t/\partial v_t$ in the *port-hinterland traffic submodel*), the nonfreight road traffic flow, and the nonfreight value of time.

3. Accident cost (AC). Traffic accidents occur along with freight traffic flow. Accident cost is calculated based on freight traffic volume (v_t), average accident probability, and the average single accident loss (values of the latter two parameters refer to (Zhang et al., 2013)).

3.3. Model implementation

3.3.1. Implementation of the integrated model framework

The five constituent submodels interact in an iterative manner; that is, the results from the previous period of time affect the calculation of the next period of time. In this manner, the holistic and dynamic impact of the modal shift policy mix can be captured. Due to this feature, the system dynamic approach is employed to implement the integrated framework given its capability to address dynamically intertwined issues. Fig. 4 shows a simplified stock and flow diagram of the proposed model framework, which is implemented using the Vensim DSS® software package (Ventana Systems, Inc., Harvard, MA, USA).

The implemented model maintains a similar structure to the framework in Fig. 3, and it is developed in a stepwise calculation manner based on the proposed Eqs. (1)-(7). For example, Eq. (1) is an integrated econometric model for port throughput estimation. In Vensim DSS®, two stock variables are defined first to represent the import and export (IE) and gross industrial product (GIP) values, as expressed as follows:

$$\text{Import and Export} = \text{INTEG (Increase of IE, Initial IE value)} \tag{8}$$

$$\text{Gross Industrial Product} = \text{INTEG (Increase of GIP, Initial GIP value)} \tag{9}$$

where INTEG represents integral calculation and all the variables are defined in an explanatory way. On this basis, Eq. (1) is

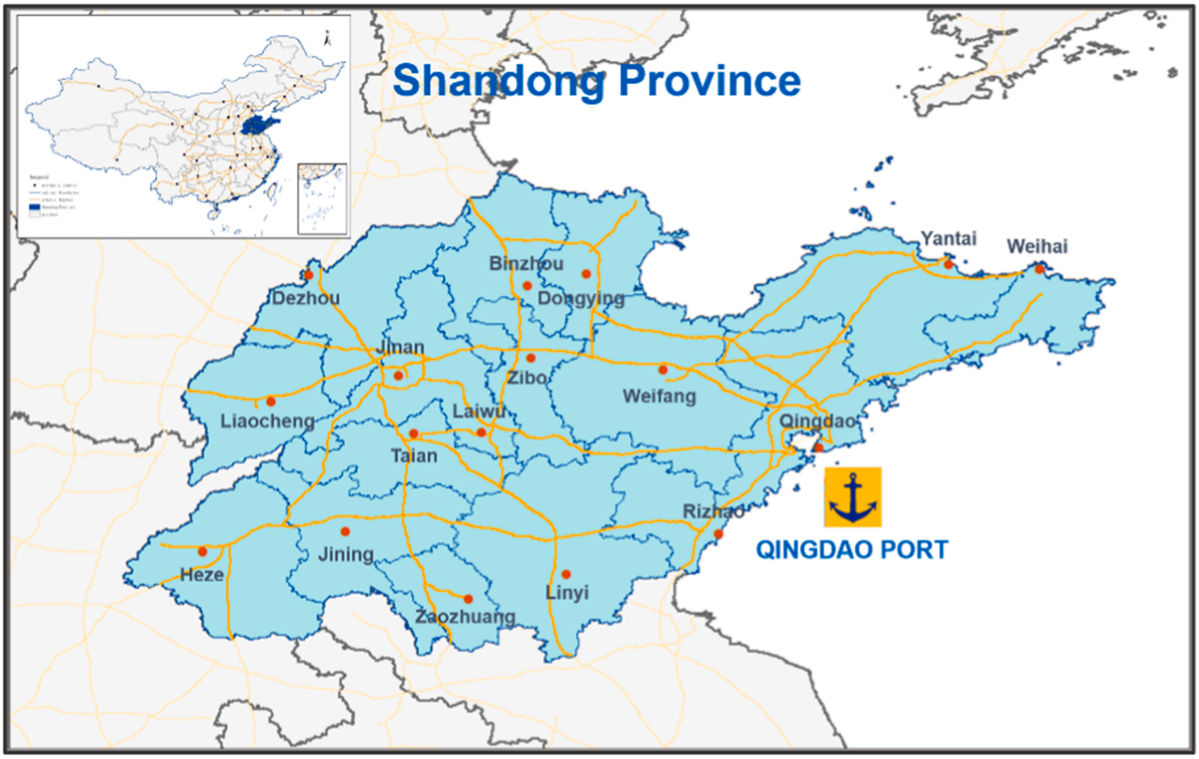

Fig. 5. Illustration of Qingdao Port and its major hinterland in Shandong Province.

subsequently implemented.

Eq. (2) shows an integrated calculation process for railway freight volume. In the implemented model, an auxiliary variable is defined first to represent the scheduled railway freight volume, as expressed in Eq. (10).

$$\text{Scheduled railway freight volume} = \text{Port throughput} * \text{Railway mode share} \tag{10}$$

where Port throughput and Railway mode share correspond to PT_t and r_t^{RW} in Eq. (2). Next, another auxiliary variable is defined to represent the actual railway freight volume, as expressed in Eq. (11).

$$\text{Actual railway freight volume} = \text{MIN}(\text{Scheduled railway freight volume}, \text{ Railway capacity}) \tag{11}$$

where Actual railway freight volume denotes f_t^{RW} in Eq. (2). In Appendix A1, the implementation of a more detailed stock and flow diagram is presented.

3.3.2. Implementation of the Monte Carlo simulation

To address the uncertainty in both hinterland economies and modal shift policy instruments, Monte Carlo simulations based on the implemented system dynamic model are employed. In this study, the scenario exploration workbench developed by Kwakkel (2017) (available on GitHub, https://github.com/quaquel/EMAworkbench) is used to perform Monte Carlo simulations. This workbench interfaces with the system dynamic model via the DLL (dynamic link library) file exported by the Vensim DSS®. Thus, it conducts a series of computational experiments that cover how the various uncertainties might be resolved. Moreover, this workbench supports scenario discoveries, which can determine the range of exogenous parameters that lead to a designated range of output. We adapted this general workbench to our proposed model by changing the codes related to model linkage and input parameters. Thus, this adapted workbench enables the formulation of modal shift policy mixes for the sustainability of port-hinterland transport.

4. Model application

4.1. Case profile and parameter setting

To demonstrate the proposed methodology, the Qingdao Port in China and its land freight system are taken as an application case, as illustrated in Fig. 5. Qingdao Port is the eighth largest port worldwide in terms of throughput. The major hinterland of Qingdao Port is Shandong Province. In 2018, Shandong Province initiated an important long-term economic upgrade that involves the *Kinetic Conversion from Old to New Industries (*KCONI) (Shandong Provincial People's Government, 2018), which aims to reduce traditional coal- and metal-related industries while stimulating new high value-added industries. How to formulate modal shift policy mixes to increase the sustainability of the system while considering the hinterland economic transition is an urgent issue for provincial governments and port authorities.

To address the economy of the hinterland, the port throughput econometric model was estimated by the StataSE® 15 software package (Stata Corp, Texas, USA), as expressed in Eq. (12).

$$PT_t = \beta_0 + \beta_1 IE_t + \beta_2 GIP_t + \beta_3 RD_t + \varepsilon_t \tag{12}$$

where β_i represents the regression coefficients, and ε is a disturbance term. PT_t, IE_t, GIP_t, and RD_t denote port throughput, imports and exports, gross industrial product, and road mileage, respectively. Data were obtained from official statistics (Shandong Provincial People's Government, 2018; Wind Database, 2021). The estimation results in Table 1 indicate that the selected economic indicators are highly correlated with port throughput. Detailed results of model verification tests are available in Appendix A1 due to space limitations.

To address the uncertainty in the economic transition in the hinterland, three economic scenarios are defined. Different values regarding economic indicators are assigned to reflect different economic prospects, as specified in Table 2. Eq. (12) transforms the change in economic prospects into the change in port throughput.

In this case, four modal shift policy instruments are considered, as specified in Table 3.

4.2. Model validation

The proposed model framework is validated through a series of validation tests. This study follows the classic system dynamic

Table 1
Regression results for port throughput estimation.

	Dependent variable: *PT*					
—	Coef.	St. Err.	t	P>| t |	95%Conf.Interval	
IE	0.051***	0.010	4.99	0.000	0.029	0.073
GIP	0.111***	0.012	9.60	0.000	0.086	0.135
RD	0.278***	0.075	3.71	0.002	0.118	0.440
ε	38.36***	7.849	4.89	0.000	21.52	55.19

Notes: *, **, *** represent significance at the levels of 10%, 5%, and 1%, respectively. R Squared = 0.9978.

Table 2
Definition of different economic scenarios.

Scenario name	Scenario specification	Related parameters
Low (low economic growth)	Without continuous kinetic energy in economy, the economy of Shandong Province enters a low economic growth track.	Following the most decadent period of the economy in the past five years (2020), the import and export and gross industrial production growth rates maintained a low 1.5% and 2%, respectively.
Medium (medium economic growth)	This scenario assumes that the economic development trend follows the growth trend since the implementation of the KCONI in the past five years.	According to the goal regulated by the KCONI, the total import and export value achieves an annual growth rate of 5%. On the other hand, traditional production capacity decreases, and the industrial growth rate decreases by 0.5% annually to the objective of 2%.
High (high economic growth)	This scenario assumes an optimistic economic trend. It assumes that the economy will return to its pre-epidemic prosperity.	At the peak of the implementation of the KCONI, import and export grows by 6.4% and the planned industrial growth rate changes to 3%.

Data source: Statistical Yearbook of Shandong Province (Shandong Provincial Bureau of Statistics, 2018), and The Implementation *Plan of the Kinetic Conversion from Old to New Industries* (KCONI) in Shandong Province (Shandong Provincial People's Government, 2018).

Table 3
Specification of the constituent policy instruments in the modal shift policy mix.

Policy instruments	Policy source and intervention
IEC-based pricing. This policy charges freight carriers in the form of taxes according to the externalities during freight transport.	According to the IEC mechanism (Iannone, 2012), IEC-based pricing changes freight rate p_t in Eq. (6) by imposing additional externality-related cost on freight operation cost $O(F_t, V_t^k)$.
Road construction. One of the major issues for port-hosted cities is the congestion incurred by freight traffic associated with ports. This policy advances the construction of roads linked with Qingdao Port.	The growth of road capacity (q_t in Eq. (3)) is set at 30%, which is consistent with the requirements of the *14th Five-Year Plan of Shandong* Province (Shandong Provincial People's Government, 2021).
Railway service. A long waiting time for rail freight wagons leads to a low railway service level. This policy will facilitate collaboration among port authorities, local governments, and the China Railway Corporation to assign more rail wagons.	According to the *Integration between Qingdao Port and Inland Cities* strategy, launched by Qingdao Port (Qingdao Municipal People's Government, 2021), more rail freight wagons will be allocated, and the departure frequency of freight trains will increase by 20%. This will reduce railway time cost in Eq. (3).
Railway subsidy. This policy will extend railway freight rate advantage by providing railway subsidies.	The *Integration between Qingdao Port and Inland Cities* strategy also proposed subsidies for railway, capped at 30% of freight rates. (Qingdao Municipal People's Government, 2021). This is reflected by S in Eq. (5).

validation procedure proposed by Barlas (1996), who recommended three sequential categories of tests for validation: direct structure tests, structure-oriented behavior tests, and behavior pattern tests. The first two categories of tests evaluate the validity of model structures, and the behavior pattern tests measure how accurately the model can reproduce the major behavior patterns exhibited by the real system. In particular, the historical data of the Qingdao Port case are compared with the model estimated values for behavior pattern tests. Moreover, the proposed model is applied to another case, the Shanghai Port case, which has different features from the Qingdao Port case in terms of both the hinterland economy and the port-hinterland transport modes. By comparing the output, the

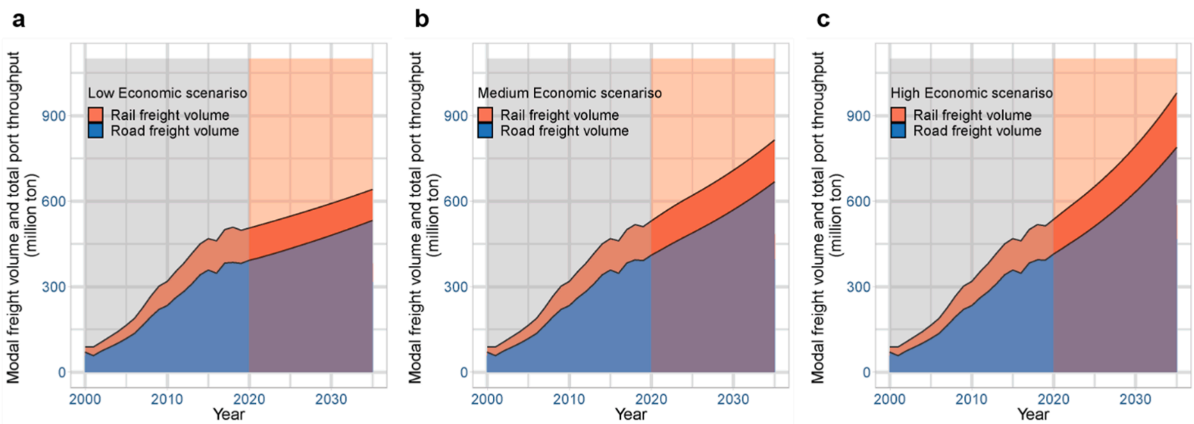

Fig. 6. Projection of port throughput and modal freight volume trends under the (a) *Low*, (b) *Medium*, and (c) *High* economic scenarios. Note: Road freight plus railway freight represents port throughput, in which liquid bulk through pipelines is excluded. The simulation period ends in 2035, which conforms to the implementation plan of the KCONI (Shandong Provincial People's Government, 2018). The results with a gray background are the actual historical values. The results with an orange background are the values projected by the model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

advantages and adaptability of the proposed model are demonstrated; this also serves as one of the modified behavior tests. Detailed results of these validation tests are presented and explained in Appendix A2.

5. Results

5.1. Port throughput and modal freight volume

Long-term trends of the throughput of Qingdao Port in different economic scenarios are projected. The aggregate port throughput is subsequently assigned to road and railway freight according to the estimated modal split ratios. These results are shown in an integrated manner in Fig. 6, in which road freight plus railway freight represents port throughput.

Overall, Fig. 6 shows a significant variance in port throughput under different economic scenarios. In the *Medium* scenario (Fig. 6b), port throughput grows steadily in the future, increasing by approximately 50% until 2035 compared to 2020. Taking the *Medium* scenario as a reference, the growth of port throughput slows in the *Low* scenario (Fig. 6a) due to the lack of kinetic energy in the economy and the spread of the COVID-19 pandemic, which causes a standstill in economic growth (Cui et al., 2021). In contrast, the *High* scenario (Fig. 6c) extricates economic development from the adverse conditions induced by the pandemic and assumes that the economic transition in Shandong Province succeeds. In this prospect, the throughput of Qingdao Port will reach a milestone of one billion tons in the long term.

Fig. 6 also exhibits the trends in the freight mode share. Shippers prefer road transport in all three economic scenarios. Road transport accounts for over 80% of the total freight due to its agility in services. Without policy intervention, road freight volume in the future still rises even though its growth may cause congestion. Considering that the railway operation cost is lower, this result indicates that the low railway service level (a long dwelling time) is a major disadvantage causing its low mode share.

5.2. Externality of port-hinterland transport without policy intervention

Based on the estimated modal freight volumes, long-term trends of port-hinterland transport externalities are projected. The results are illustrated in Fig. 7 in terms of external monetary costs.

Fig. 7 shows that the trends of total external costs under different economic scenarios are not proportional to the trends of port throughput in Fig. 6. This result is primarily attributed to the inefficiency in road transport, which is caused by both the increase in total freight demand (port throughput) and the high road mode share. Therefore, congestion occurs more frequently, increasing road users' time costs and incurring emission costs on society. Particularly in the *High* scenario, in which the freight flow increases by 90% until 2035 compared to 2020 (see Fig. 6c), the congestion cost increases dramatically by more than twofold in 2035 (see Fig. 7c). This indicates that road traffic will exceed the upper limit of the road network carrying capacity and cause severe congestion.

5.3. Externality mitigation by modal shift policy mix

The effects of the proposed modal shift policy mix (as specified in Table 3) on reducing transport externalities under three economic scenarios are compared and demonstrated as bridge charts in Fig. 8.

In Fig. 8, the left two columns in each chart represent the total external costs in 2020 and 2035. These results are consistent with the projection of the total external cost shown in Fig. 7. The columns on the right show the additional effects on mitigating externalities until 2035 when the respective policy instruments superpose. Three features of the results are noteworthy.

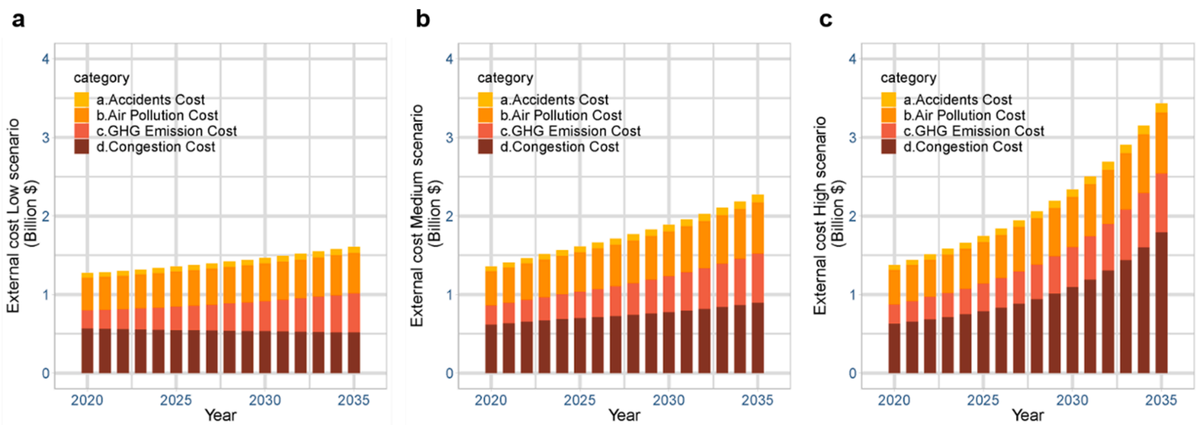

Fig. 7. External costs of port-hinterland transport under the (a) *Low*, (b) *Medium*, and (c) *High* scenarios without policy intervention.

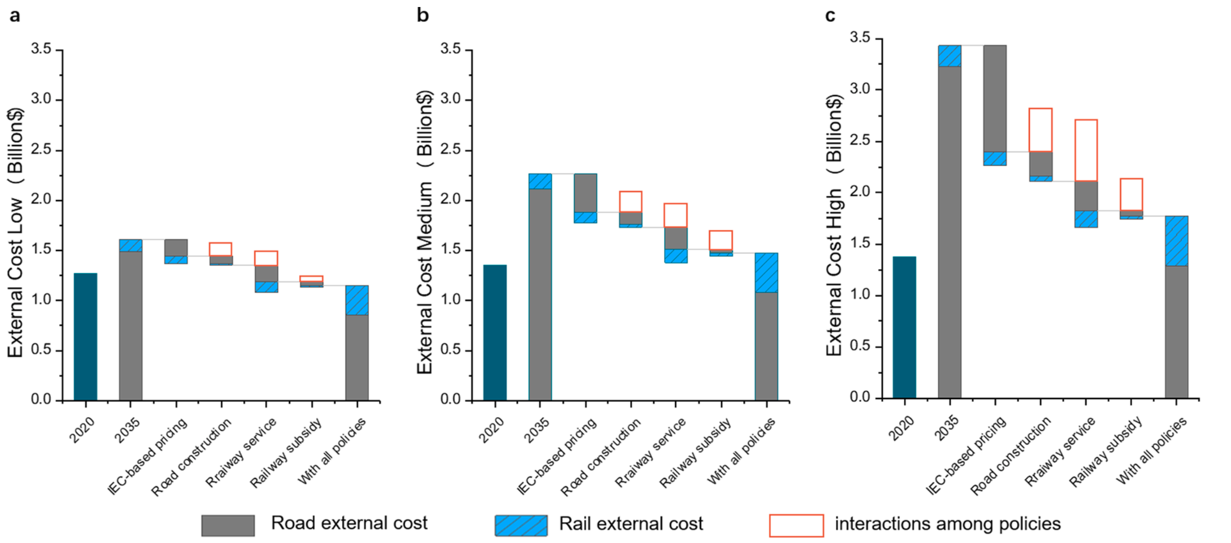

Fig. 8. Effects of externality mitigation by the modal shift policy mix under the (a) *Low*, (b) *Medium*, and (c) *High* economic scenarios.

- The overall efficacy of the modal shift policy mix increases with the increase in freight demand associated with economic growth. Compared to the value without policy intervention in 2035 (the left second column), the total external cost decreases by 35%, 40%, and 52% in the three economic scenarios (the first column on the right in Fig. 8a, b, and c, respectively).
- IEC-based pricing shows a significant effect in reducing externalities in all three economic scenarios (see the third column on the left in Fig. 8a, b, and c). Its efficacy in reducing externalities is particularly evident in the *High* economic scenario, in which the total freight demand is high and IEC's potential in adjusting the competitiveness condition between road and railway is fully exploited.
- Increasing the railway service level also exhibits an evident contribution to externality mitigation (see the left fifth column in Fig. 8). Transport mode competitiveness is determined by not only the operation cost but also the service level. The results show that the railway freight rate is low, but the mode share is not high (Fig. 6). Thus, the railway service level plays a dominant role in determining its mode share. This also explains why increasing the railway service level shows greater potential for externality mitigation than does proposing a railway subsidy (see the left sixth column in Fig. 8).

Fig. 8 also shows that the holistic effect of a policy mix is not a simple superposition of the effects of multiple policy instruments but involves interactions in between because these policies share the goal of facilitating modal shifts. To better illustrate these interactions, both decreases and increases in transport externalities are shown in Fig. 9.

In Fig. 9, three economic scenarios are differentiated using different background colors. The first row in each scenario category shows the total cumulative externality change, and the following four rows illustrate the constituent four types of externalities. Within each row, there are two subrows demonstrating the changes in cumulative externalities associated with roads and railways. Furthermore, all these externalities are attributed to their causal policy instruments. Two features of the results are noteworthy.

- Regarding the total externality, as the policy mix generally achieves a freight modal shift from road to railway, the externality associated with road transport is reduced along with the increase in railway externality. Since railways are more efficient in freight transport, the reduction in road externalities is greater than the increase in railway externalities (Li and Zhang, 2020). This effect becomes more evident with the increase in total freight volume. Therefore, in the context of economic growth in port hinterlands, the increase in port throughput calls for a more complete sea-rail intermodal freight system.
- Regarding specific types of externalities, the increase in railway externalities originates from the shifted freight demand from roads, which primarily leads to an increase in emission costs due to the increase in railway traffic. Thus, to further enhance the overall efficacy of the policy mix, increasing energy efficiency in railway transport (by technology improvement) is an efficient approach.

6. Discussion

6.1. Formulating modal shift policy mixes for sustainable port-hinterland transport

The above analyses show the trends of port-hinterland transport externalities under certain policy mixes. Nonetheless, the strength of policies (e.g., the amount of subsidies and investments) in the future is subject to change. This study further considers the uncertainty in both the strength of policies and hinterland economic prospects and conducts global uncertainty analysis using Monte Carlo simulation. The results are shown in Fig. 10a. The results show that externalities in the future vary over a wide range considering the uncertainty in hinterland economic prospects and policies. Overall, externalities increase with economic growth. Regarding different

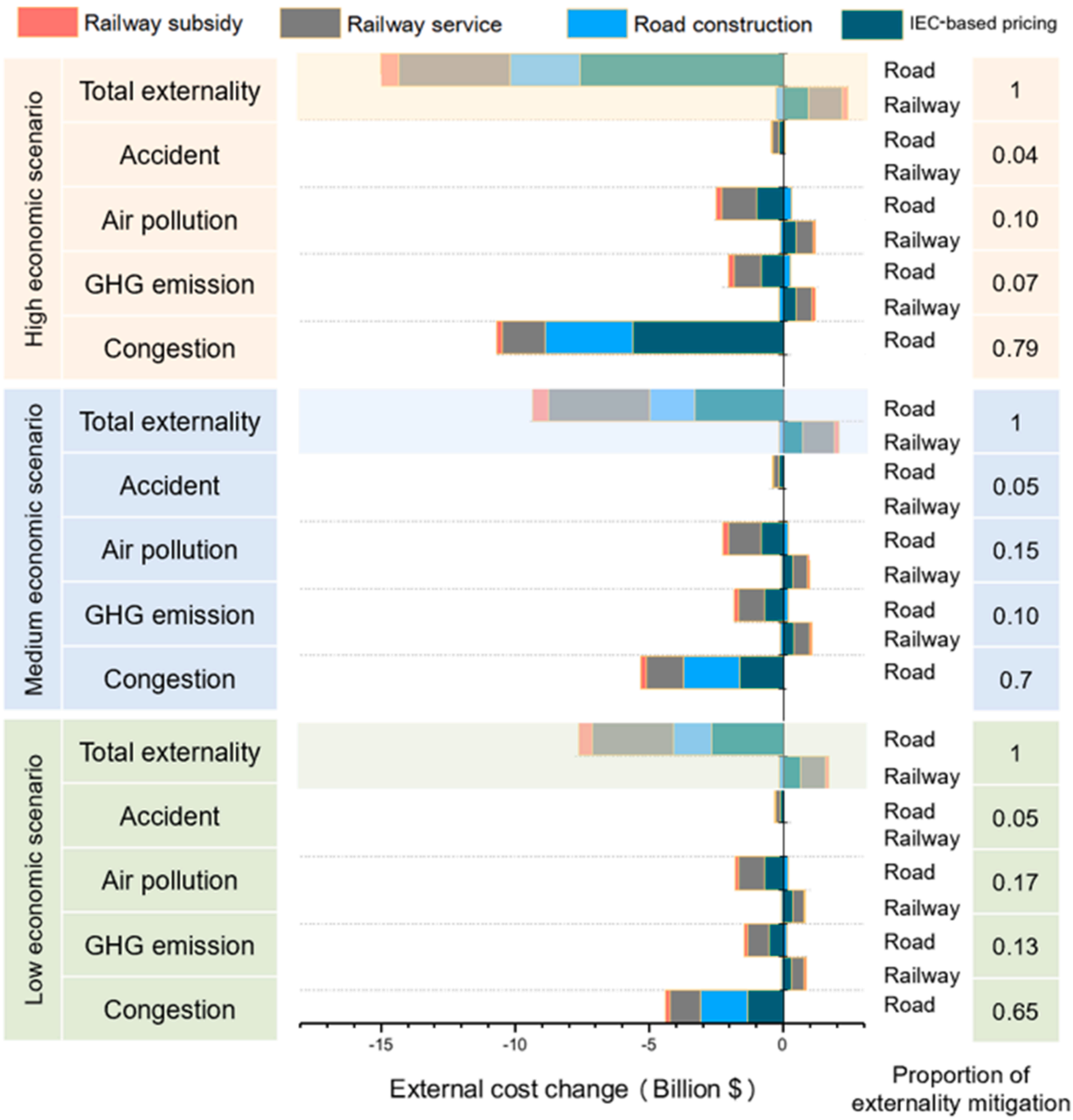

Fig. 9. Interactions in the modal shift policy mix. Note: Interactions are demonstrated by the structural changes in the cumulative externality during the simulation period (2020–2035).

economic prospects, modal shift policy mixes with better sustainable performance (the lowest 20% of externalities) are identified, as shown in Fig. 10b-d.

The results show that despite the significant uncertainty of hinterland economic prospects, the policy mixes to increase sustainability are basically robust. IEC-based pricing and increasing railway service are two common instruments in all three economic scenarios. This result is consistent with the result shown in Fig. 8, in which these two instruments show the most evident effect in reducing externalities. Furthermore, the specific strength of policy instruments is also determined. IEC-based charging (per ton-kilometer) on different transport modes should be at least approximately 40% of the respective modal externalities (per ton-kilometer), and the railway service level should be raised at least approximately 10%. In addition to these two highest-priority instruments, the third policy instrument depends on economic prospects. Under the *Low* and *Medium* economic scenarios, railway subsidies are preferred. In the *High* scenario, the decision maker should consider road construction.

6.2. Suggestions for model adaptation and implications for policy making

The results of the case study show the capability of the methodology in formulating modal shift policy mixes based on analyses of

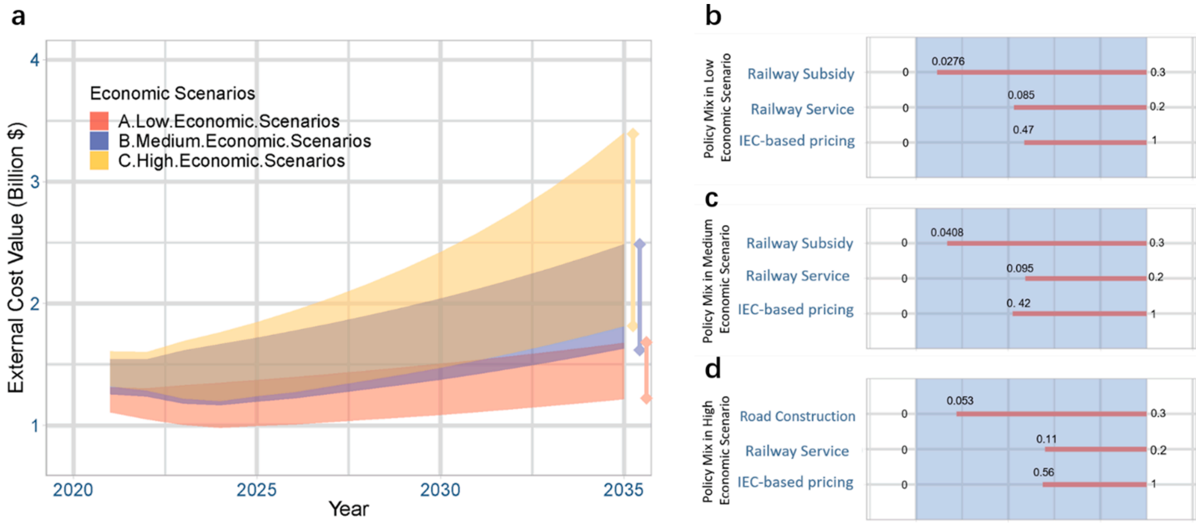

Fig. 10. (a) The results of uncertainty analysis and modal shift policy mixes under the (b) *Low*, (c) *Medium*, and (c) *High* economic prospects.

the holistic impact of policy mixes. Regarding other port-hinterland transport systems, implications for policy making and suggestions for model adaptation are provided in the following.

First, modal shift policy mixes for sustainable port-hinterland transport should incorporate the economy in the hinterland in a holistic manner. The transition in the hinterland economy leads to changes in port throughput and freight demand, which further influence the multimodal port-hinterland freight system and its sustainable performance. The proposed methodology correlates the hinterland economy with port throughput using econometric models. For ports with a main business in containers and dry bulk, respectively, import and export value and the output value of heavy industries can be used as explanatory variables. In addition, more sophisticated econometric models, such as the VAR (vector autoregression) and ARDL (autoregressive distributed lag) models, may estimate port throughput more accurately (Liu et al., 2021; Rashed et al., 2018). Subsequently, a port-hinterland transport model transfers changes in port throughput into changes in transport externalities. This model is adapted based on the four-step transport framework. Specifically, it is implemented using the system dynamic approach, which not only captures the holistic impact of modal shift policy mixes but also supports the design of policy mixes by performing Monte Carlo simulations.

Second, modal shift policy mixes for sustainable port-hinterland transport should consider both the efficacy and feasibility of policy instruments. The modal shift policy mixes of the case study are formulated based on the efficacy of policies in reducing externalities. To determine the effectiveness of policy instruments, their implementation costs must be considered (Nocera et al., 2015). Regarding the case of this study, the cost-benefit analysis shows that the benefits (externality reduction) of railway subsidies, increasing railway service levels and road construction are lower than the costs of policy implementation, while IEC-based pricing bridges this cost-benefit gap and increases the feasibility of policy mixes (detailed results are available in Appendix A3). IEC-based pricing has been implemented in some European regions (Kaack et al., 2018), but it has yet to be implemented in China. Nonetheless, according to China's measures to realize the goals of carbon peaks and carbon neutrality, it will probably be put into effect in the form of a carbon tax, which has similar effects.

Third, analyzing the interactions among constituent policy instruments is conducive to designing modal shift policy mixes and increasing their efficacy. The proposed methodology supports the design of policy mixes, but constituent policy instruments must to be predefined. Analyzing the interactions among policy instruments is conducive to identifying additional policy instruments to increase the overall efficacy of the policy mix. For example, the results of the case study show that there are conflicts among the effects of multiple modal shift policies (see Fig. 9). A reduction in road transport externalities is achieved along with an increase in railway transport externalities. Therefore, to enhance the efficacy of modal shift policy mixes, introducing technology improvement to reduce railway-related externalities will be more efficient.

7. Conclusion and future work

The sustainable performance of port-hinterland transport is determined by multiple interrelated factors, such as the economy of the hinterland, freight flows, transport infrastructure, and policies. This study advances the literature by proposing a holistic approach to facilitate the design of modal shift policy mixes for sustainable port-hinterland transport. This approach integrates econometric estimation, system dynamic modeling, and Monte Carlo simulation to address the economy of the hinterland, port-hinterland transport and policy mixes in a holistic manner. The proposed methodology is applied to Qingdao Port and its inland freight system in China. Notable results and insights are summarized as follows.

- The economic prospects of the hinterland show a significant impact on port throughput and the sustainable performance of port-hinterland transport. Particularly in the optimistic *High* economic scenario, the expansion of port freight demand stretches the hinterland freight system and causes a disproportional increase in freight externalities. Policy intervention is more necessary to facilitate sea-rail intermodal freight.
- The holistic effect of the modal shift policy mix is investigated. The policy mix's efficacy in reducing externalities increases with the increase in freight demand, but the holistic effect of the policy mix is lower than the sum of the effects of individual policies because these policies share the goal of facilitating modal shift.
- Modal shift policy mixes with better sustainable performances are identified. Regarding the Qingdao Port case, despite the uncertainty for hinterland economic prospects, policy mixes with better performances in reducing externalities commonly include IEC-based pricing and increasing the railway service level. The third constituent policy instrument depends on hinterland economic prospects.

This study proposes an integrated model framework to assess the holistic impact of the modal shift policy mix and to optimize the mixes of modal shift policies to increase the sustainability of port-hinterland transport. However, constituent policy instruments must be predefined by decision makers. In addition, clean fuels or alternative power in road fleets and port operations are not considered. Thus, future work can be extended in two directions. First, scenario exploration methods can be introduced to discover potential modal shift policies. Second, technology penetration or diffusion models can be incorporated to assess the impact of technology-related instruments on the sustainable performance of port-hinterland transport.

CRediT authorship contribution statement

Taolei Guo: Data curation, Formal analysis, Writing – original draft. **Pei Liu:** Conceptualization, Methodology, Writing – review & editing, Visualization, Supervision. **Chao Wang:** Conceptualization, Writing – review & editing. **Jingci Xie:** Data curation, Writing – review & editing. **Jianbang Du:** Validation, Writing – review & editing. **Ming K. Lim:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2023.103746.

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