



# Sustainable linear infrastructure route planning model to balance conservation and socioeconomic development

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## ARTICLE INFO

### Keywords:

Linear infrastructure  
Route planning  
Scenario setting  
Least-cost path  
Sri Lanka

## ABSTRACT

Linear infrastructures, such as roads, highways and railways, can bring significant social and economic benefits while posing great threats to local environment and biodiversity. Although processes such as Strategic Environmental Assessment have been increasingly applied during the route planning stage of major linear infrastructures to evaluate their potential impacts, the assessment of the spatial variations in these impacts is often missing. Thus, a spatial planning tool that balances both the costs and benefits for environmental and socioeconomic aspects is needed. Here we propose a Sustainable Linear Infrastructure Route Planning Model, which incorporates the spatial assessments of potential environmental and socioeconomic impacts using factors from six aspects, which are ecosystem importance, biodiversity conservation, environmental risks, economic costs, social costs, and socioeconomic benefits. The model allows users to set weights for different factors according to specific development priorities, then produces a weighted spatial resistance map, and identifies the optimized route through least-cost path analysis. We implemented this model through a case study of the Southern Expressway Extension project in Sri Lanka to test its validity. The results showed that the route choices from our model under three hypothetical scenarios (environmental, socioeconomic and balanced) all resulted in lower negative impacts compared to the current route. The proposed model can provide decision-makers an effective tool to improve the sustainability of roads, highways and railways in the age of rapid linear infrastructure expansion across the globe.

## 1. Introduction

The development and prosperity of human society rely on supports from various infrastructures. One type of such infrastructure, linear infrastructure (e.g. roads, highways and railways) on one hand can bring significant social and economic benefits, such as the promotion of resource utilization, trading, and connectivity (Iacono and Levinson, 2016; Wang et al., 2020). As a result, linear infrastructure construction became a major focus for social and economic development across the globe (Laurance et al., 2014). On the other hand, despite the great economic benefits linear infrastructures could bring, significant ecological and environmental problems were also caused by them. There is mounting evidence showing that linear infrastructures can increase habitat loss and fragmentation, landslide susceptibility, wildlife-vehicle and -train collision, poaching and illegible harvesting (Kirschbaum and

Stanley, 2018; Claireau et al., 2019; Ng et al., 2020). For instance, it was found that approximately 95% of all deforestation occurred within 5.5 km of roads in Amazon forests (Barber et al., 2014). Moreover, in some areas of Alaska, moose populations could decline by 70% due to wildlife-train collision (van der Ree et al., 2015). The extent and intensity of the negative impacts of linear infrastructures are determined by various characteristics such as adjacent landscape, topography, hydrography, vegetation type, habitat quality (van der Ree et al., 2015). Therefore, it is crucial to find a route planning strategy that can consider these characteristics in order to minimize ecological and environmental impacts while maximizing socioeconomic benefits simultaneously for promoting the sustainability of linear infrastructures (Jaeger, 2015; Zhang et al., 2015).

To achieve this goal, more and more countries are now applying the Strategic Environmental Assessment (SEA) for major linear

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<https://doi.org/10.1016/j.biocon.2022.109449>

Received 24 August 2021; Received in revised form 26 December 2021; Accepted 1 January 2022

Available online 11 January 2022

0006-3207/© 2022 Published by Elsevier Ltd.

infrastructure projects during their route planning stage (van Doren et al., 2013). Compare to the project-based Environment Impact Assessments process, SEA is implemented at an earlier stage of policies, planning and decision-making in order to improve the efficiency of environmental assessment and promote sustainability at a larger scale (Bonifazi et al., 2011; Jaeger, 2015). However, for linear infrastructure projects, studies have shown that current SEA processes often fail to include a full range of potential environmental, ecological, social and economic impacts from projects in practice (Chaker et al., 2006; Mörtberg et al., 2007; van Doren et al., 2013). For instance, SEA of land use plans in Finland was very narrowly focused when considering biodiversity impacts. It only evaluated the impacts on some common species while ignoring others to avoid legal challenges (Söderman and Saarela, 2010). More recently, Gutierrez et al. (2021) also reported a lack of integration of ecosystem services and biodiversity at the early stage of SEA process after assessing six SEAs conducted for urban development plans across Australia. In addition to this problem, the current SEA processes also lack the consideration of spatial variation during the impact assessment. An earlier study showed that the spatial differences in potential impacts on biodiversity from large-scale development projects are greatly missed in current SEA processes in Western Australia (Whitehead et al., 2017). These shortcomings of the SEA can lead to inappropriate route choices for linear infrastructures, which might lead to not only the abovementioned environmental and conservation problems but also socioeconomic challenges such as significant economic costs (Tijanić et al., 2020), protests from local communities (Touzi et al., 2016) and possible acceleration of diseases spreading (Millar et al., 2018).

In recent years, the need for a comprehensive and spatial-sensitive linear infrastructure route planning tool has become even more urgent due to the “Belt and Road Initiative” (BRI) proposed by China. The BRI is the largest infrastructure development initiative in human history (Lechner et al., 2018). It lists highways and railway construction as one of its most pivotal investment priorities and has already commenced and/or finished at least 20 national-level linear infrastructure construction projects in over 20 countries by 2019 (OLGPBRI, 2019). As many of the BRI participating countries are also located in the global terrestrial and marine biodiversity hotspots, there is a strong need to make BRI projects more sustainable to avoid potentially devastating impacts on both environment and biodiversity (Lechner et al., 2018). In 2017, four ministries of China - Environmental Protection, Foreign Affairs, Commerce, and National Development and Reform Commission announced an important joint statement to promote the idea of “green” BRI to reduce environmental impacts and specifically listed the construction of sustainable infrastructure as one of the main tasks (MEP et al., 2017). One of the attempts to balance development and conservation is a proposed global strategy for road building, which is based on criteria such as terrestrial biodiversity level, key habitats, wilderness, environmental services provision ability, and agricultural intensification potential (Laurance et al., 2014). However, there is still a gap in applicable regional-level route planning strategies that can comprehensively evaluate the impacts and sustainability of different route plans in real practice.

In order to fill the urgent needs for more sustainable linear infrastructure, especially in the BRI countries, here we proposed a regional-focused Sustainable Linear Infrastructure Route Planning Model (SLIRPM), which includes the spatial assessment of both ecological/environmental impacts and socioeconomic benefits. The model involves four key steps, which are the delineation of potential route zone, development of spatial resistance maps with the consideration of both environmental and socioeconomic factors, different scenarios setting based on development priorities, and identification of the optimal route through least-cost path analysis. In addition, we also illustrate the validity of the model by using the Southern Expressway Extension project in Sri Lanka as a case study.

## 2. Methods

### 2.1. General framework

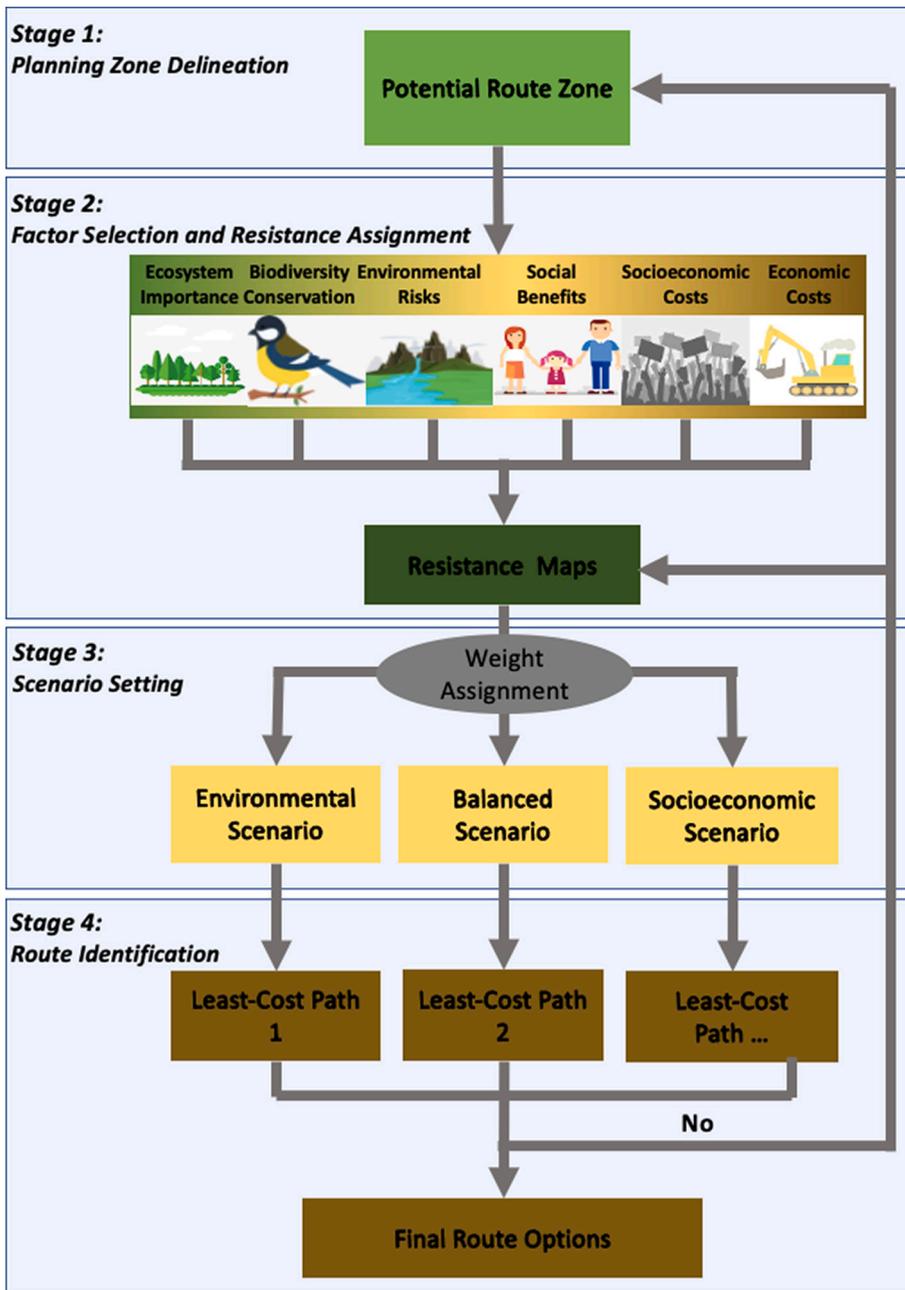
The general goal of the Sustainable Infrastructure Spatial Planning Model is to identify the optimal pathway considering both socioeconomic and environmental aspects (Fig. 1). In order to achieve this goal, the SLIRPM consists of four major steps as follows:

1. **Planning Zone Delineation:** First, identify control points, which represent the locations that the proposed linear infrastructure must pass. For instance, the starting and destination places are two control points that every proposed linear infrastructure would have. More control points can be added to any places where the stakeholders deem essential for the route to pass through, such as important towns/cities, intersections and scenic spots. Second, create buffer areas along the route with a certain radius between every two control points (in our case study, we applied half of the distance between two control points as the buffer radius as an example). Then the buffers between different control points should be merged as the potential route zone, which is the area where the route can potentially be in. The delineated potential route zone can be revised based on the needs of further assessment.
2. **Factor Selection and Resistance Assignment:** Acquire the spatial data of various factors needed to be considered for route planning and assign resistance scores to them. The selected factors should be able to reflect the potential impacts of linear infrastructures on a wide range of aspects. Not only the impacts on ecological and environmental aspects (e.g. ecosystem importance, biodiversity conservation and environmental risks) but also on social and economic aspects (e.g. economic costs social costs, socioeconomic benefits) should be covered. After the considering factors are determined and relevant data were acquired, we would obtain the resistance maps of these factors by assigning resistance scores to each factor within every buffer between two control points instead of within the whole potential route zone. Because routes are determined in the buffer area between every two control points, assigning the resistance scores in the whole zone might conceal the areas with relatively higher or lower resistances between two points.
3. **Scenario Setting:** Set up different scenarios by assigning weights to each factor. The weight of factors can be determined by stakeholders to reflect different development priorities. Overall resistance maps are created by summing up individual resistance maps of factors under different weights.
4. **Route Identification:** Apply the least-cost path analysis on the overall resistance maps to determine the routes that can minimize biodiversity and environmental impacts while maximizing socioeconomic benefits under different scenarios. Repeat the whole process in a larger potential route zone if there is no suitable route identified in the current round.

### 2.2. Considering factors

To assess the potential environmental, social and economic impacts from linear infrastructure comprehensively, a total of 23 factors from six categories were considered (Table 1). The categories include ecosystem importance, biodiversity conservation, environmental risks, economic costs, social costs and socioeconomic benefits. The ecosystem importance, biodiversity conservation and environmental risks factors mainly aim to assess the ecological and environmental impacts from linear infrastructures; while the economic costs, social costs and socioeconomic benefits factors focus on evaluating the social and economic effects. The selection of factors was mainly based on literature review and practicability.

The first goal of our proposed route planning model is to reduce linear infrastructures' impacts on ecosystem integrity and services,



**Fig. 1.** The framework of the Sustainable Linear Infrastructure Route Planning Model. The model contains four major steps: 1) planning zone delineation by creating buffers between control points; 2) route considering factor selection and resistance score assignment; 3) scenario setting by assigning different weights to factors; and 4) route identification through least-cost path analysis. The whole process can be iterated until the agreements of final route options are reached by relevant stakeholders.

which is measured through ecosystem importance. Since areas with high wilderness degree, natural vegetation (e.g. no cropland included) productivity, habitat fragmentation and restoration priority possess greater ecological importance (Chi et al., 2018; Di Marco et al., 2019; Strassburg et al., 2020), these three factors were used in our model to reflect the potential effects on ecosystems from linear infrastructures (more detailed rationales for choosing every factor can be found in the supplementary materials). For biodiversity conservation, we considered the coverage of key biodiversity areas (KBA), coverage of protected areas (PA), endangered species richness and species rarity scores, which measures endemism, to reflect the potential impacts on biodiversity (Burlakova et al., 2011; Laurance et al., 2012; Stuart et al., 2018). The first two factors mainly assess potential impacts on important habitats and the endangered species richness and rarity demonstrate the vulnerability of a place to future extinction (Burlakova et al., 2011; Li et al., 2013; Laurance et al., 2014). To minimize the impacts of linear infrastructure on other environmental factors, such as water, soil and

terrain stability, the proximity to rivers, landslide susceptibility and soil erosion susceptibility were selected to reflect these potential environmental risks (Seutloali and Reinhard Bechedahl, 2015; Kirschbaum and Stanley, 2018; Grill et al., 2019).

In terms of socioeconomic impacts, studies showed that linear infrastructures with shorter length, in areas with flatter terrain and less deformable subgrade material (i.e. lower content of soil organic matter and clay) or used existing linear infrastructures could lead to significantly lower economic costs (Mahamid, 2011; Tang et al., 2016; Tijanić et al., 2020). Thus, we selected the total length of the route, slope suitability, soil suitability and road (railway) density in the potential route zone to identify areas with higher construction suitability to minimize the economic costs of projects. To minimize potential social costs of linear infrastructures, areas with higher wildlife-human disease transmission risks, more important cultural heritage sites and lower public support for linear infrastructure construction are not preferred because it is assumed that crossing such areas would lead to more

**Table 1**

The descriptions, assumptions and data sources of the 23 proposed factors in the Sustainable Linear Infrastructure Route Planning Model.

Categories	Factors	Descriptions	Assumptions for route avoidance	Data source used in case study
Ecosystem importance	Wilderness	Intensity of human influences in a unit area	Areas with lower human influences can serve as better habitats for more wildlife species (Di Marco et al., 2019).	Riggio et al. 2020
	Natural vegetation productivity	Net primary productivity of natural vegetation types	Areas with higher vegetation productivity indicate better vegetated ecosystem quality (Chi et al., 2018).	MODIS dataset of 2015: MOD13A3HGF v006
	Habitat fragmentation	Area size of habitat patches	Larger habitat patches indicate lower fragmentation levels (Haddad et al., 2015).	Land cover data of 2015 from ESA Climate Change Initiative Ecosystem Cover Project
	<i>Habitat connectivity</i>	Corridors that connect different populations	Areas that used by wildlife species as corridors or stepping stones are important for maintaining population size (Park, 2015; Zhu et al., 2021)	N/A Possible data source: expert knowledge, landscape connectivity model
Biodiversity Conservation	<i>Ecological restoration priority<sup>a</sup></i>	Restoration priority for biodiversity and mitigate climate change	Areas with higher ecological restoration priority possess higher ecological and environmental benefits (Strassburg et al., 2020).	N/A Possible data source: Local priority setting
	Habitat importance	Areas designated as Key Biodiversity Area (KBA)	Areas designated as key biodiversity areas indicate high biodiversity conservation value (Stuart et al., 2018).	The KBA Programme/Environmental Impact Assessment report
	Endangered species richness	Richness of vulnerable, endangered and critically endangered species in a unit area	Areas with more endangered species are more vulnerable to biodiversity loss.	International Union for Conservation of Nature (IUCN) species list
	Species rarity <sup>b</sup>	Rarity of species found within potential route zone	Areas with more endemic species are more vulnerable to species extinction loss (Burlakova et al., 2011; Li et al., 2013).	International Union for Conservation of Nature (IUCN) species list
	Protected status	Areas designated as Protected Area	Areas designated as protected areas indicate high biodiversity conservation value and stronger legal protection requirements (Laurance et al., 2012).	WDPA
Environmental Risks	Proximity to rivers	Distance to the closest free-flow river	Areas with shorter distances to free-flow rivers indicate better aquatic ecosystem quality and a higher probability of flooding damage (Grill et al., 2019).	Grill et al., 2019
	Soil erosion susceptibility	Soil retention ability in a unit area	Areas with higher soil retention ability would be more negatively impacted by road construction and more susceptible to erosion (Jungerius et al., 2002; Seutloali and Reinhard Beckedahl, 2015).	INVEST model Sediment Delivery Ratio Module
	Landslide susceptibility	Susceptibility score of landslide events in a unit area	Areas with higher landslide susceptibility would be more negatively impacted by linear infrastructure construction (Kirschbaum and Stanley, 2018).	Kirschbaum and Stanley, 2018
Economic Costs	Total length	Distance from the shortest line between control points	Areas with longer distances from the shortest line would increase construction costs (Mahamid, 2011).	GIS analysis
	Slope suitability	Average slope in an area	Areas with steeper terrain would increase construction difficulties (Tijanić et al., 2020).	GMTED2010
	Soil suitability	Average topsoil clay and organic carbon contents	Areas with clay- and carbon-rich soils need more treatments to be used as subgrades (Tang et al., 2016).	Global Compilation of Soil Profile data (WoSIS)
	Road/Railway density	Length of existing roads/railways in an area	Areas with higher existing road/railway density suggest more opportunities of using existing infrastructure instead of building new ones to lower construction costs (Tijanić et al., 2020) <sup>c</sup> .	Roads of 2015 in Sri Lanka from Open Street Map
Socioeconomic Benefits	Economic activity level	Average economic activity level	Areas with higher economic activity levels might receive greater economic gains from the connections to other markets by linear infrastructures (Shi et al., 2014) <sup>c</sup> .	Nighttime light used as a proxy of economic activity level in the case study: NOAA/NGDC NPP-VIIRS dataset
	Accessibility improvement potential	Access time to cities in a unit area	Areas with longer access time to cities would benefit more socially from linear infrastructure construction (Weiss et al., 2018) <sup>c</sup> .	Weiss et al., 2018
	Population density	Average number of people in a unit area	Areas with higher population density indicate higher needs for road connection and potential social gains (Bencardino and Nesticò, 2019) <sup>c</sup> .	LandScan™ global population dataset of 2015
	Land cover suitability	Land cover of urban, agricultural, forest, water and others	Areas with urban and agricultural land use types have lower construction difficulties and higher potential socio-economic benefits <sup>c</sup> . Areas with forest and water land use types have higher construction difficulties and lower potential socioeconomic benefits (Laurance et al., 2014).	Land cover data of 2015 from ESA Climate Change Initiative Ecosystem Cover Project
Social Costs	Pathogen spillover risk	Richness of bats, rodents, primates, and animals of least concern and increasing trends in a unit area	Areas with more bats, rodents, primates, and terrestrial animal species of least concern with increasing trends have higher wildlife-human disease transmission possibilities (Johnson et al., 2020).	Range maps from International Union for Conservation of Nature (IUCN)
	<i>Cultural heritage</i>	Areas with cultural and social importance	Areas of cultural heritages indicate higher cultural and social values for people (Owley, 2015).	N/A Possible data source: participatory mapping
	<i>Public support</i>	Public attitudes toward project implementation	Areas with less public support imply a lower possibility of smooth project implementation (Rogge et al., 2011).	N/A Possible data source: public opinion survey

<sup>a</sup> Italic factors are the ones not included in the Sri Lanka Southern Expressway Extension case study due to data unavailability.<sup>b</sup> Species rarity is calculated as the sum of the reciprocal of species range size.<sup>c</sup> For these factors, the assumptions are the reasons for routes to pass through.

opposition from people (Rogge et al., 2011; Owley, 2015). Meanwhile, areas with higher economic activity levels (measured through nightlight value), accessibility improvement potential, population density and land-use suitability are preferred to improve socioeconomic benefits because two of the major socioeconomic benefits of linear infrastructure are connecting people and markets (Bencardino and Nesticò, 2019; Shi et al., 2014; Weiss et al., 2018). In the case study area, urban land is deemed to be the most suitable land cover type for linear infrastructure due to its higher economic growth potential (Laurance et al., 2014). Agricultural land is the second-most suitable land cover type to increase transportation efficiency for crops (Laurance et al., 2014). Water bodies and forests are deemed to be the least and second-least suitable land cover type for linear infrastructure construction, because of their ecological importance and construction difficulty (Tijanić et al., 2020).

### 2.3. Least-cost path analysis under different scenarios

Least-cost path (LCP) analysis is a multi-criteria optimization method that can spatially identify the most favored route (i.e. the lowest resistance) between two locations on a resistance surface. It is widely used in urban planning, infrastructure design and conservation corridor creation (Bagli et al., 2011; Lee et al., 2014; Balbi et al., 2019). Due to its high reliability and spatial-sensitive nature, this method was applied to determine the optimal route in the SLIRPM. The overall resistance map used in the least-cost path analysis was calculated by adding individual resistance maps of each factor together. Each resistance map was reclassified and assigned scores from 1 to 5 (1 being low resistance and 5 being high resistance) so that factors with different dimensions could be added. For factors with discrete (i.e. categorical or ordinal) data types, resistance scores could be assigned to factors based on the classified categories or orders. For factors with a continuous data type, we could classify the data into ordered categories and assign resistance scores to each category.

Furthermore, to assess how different development priorities would affect linear infrastructure route choices, different scenarios could be created by assigning different weights to the environmental/ecological and socioeconomic factors. These weights would be multiplied with original resistance scores to give the final resistance map of each factor under various scenarios. Higher weights would give factors higher final resistance, which would increase their influences during the least-cost path analysis. Since many factors contain both environmental/ecological and socioeconomic characteristics, the categorization of factors should not be binary but in a continuous spectrum and could be reflected in weight assignment. Taking the factors of “protection status” as an example, building major roads in protected areas not only affects the natural land cover and species habitat, it also bears legal consequences. Therefore, higher weights might be needed for the factor in either scenario that prioritizes conservation or socioeconomic development. Similar situations exist in virus spillover risk, soil erosion suitability, and land cover suitability. The changes in these factors would greatly affect both natural and social systems and should be reflected in their weight assignments. (Laurance et al., 2012, 2014; Johnson et al., 2020).

### 2.4. Case study of Sri Lanka Southern Expressway Extension Project

Sri Lanka is a lower-middle-income country with an annual GDP of 84 billion US\$ and a population of 21.80 million in 2019 (The World Bank, 2021). The 96-km-long four-lane Southern Expressway Extension (SEE) is one of the priority projects of the National Highway Development Program, which connects the previous end of South Expressway in Matara and the harbour city of Hambantota (Fig. 2). It aims to facilitate connections of the southern area (including the currently underutilized Hambantota Seaport and Mattala Rajapaksa Hambantota Airport) with other provinces of the country (SASAC, 2018). This important project is also a part of BRI in Sri Lanka and used as our case study to test the validity of the proposed route planning model.

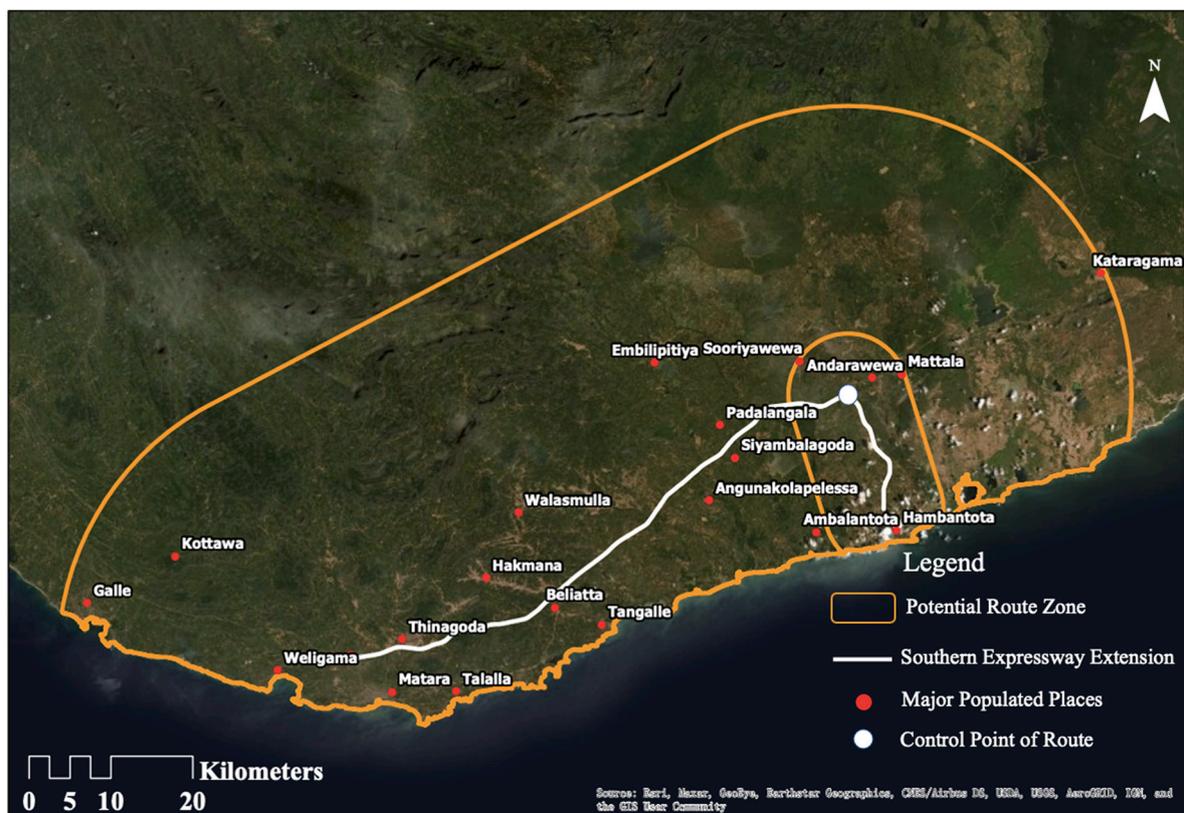


Fig. 2. Potential route zone of the Southern Expressway Extension project in Sri Lanka from Matara to Hambantota via Andarawewa.

The Southern Expressway Extension project was jointly constructed by China National Aero Technology International Engineering Corporation, China State Construction Engineering Corporation, and China Harbour Engineering Company. The construction started in January 2016 and finished in February 2020 (ColomboPage, 2020). The financing of the project was organized through the EXIM bank of China (approximately 1.9 billion US\$) together with the Sri Lanka government's contribution (15% of the total) (SASAC, 2018).

According to the Central Environmental Authority of Sri Lanka, Strategic Environmental Assessment is still only encouraged yet not mandatory for projects like the SEE. However, several Environmental Impact Assessments (EIA) were performed for the SEE project as mandated by the National Environment Act of Sri Lanka. The assessment reports raised particular concerns over the project's potential impacts on protected areas, such as the Dandeniya Aparekka forest reserve, and key animal habitats, especially for the local elephant populations (MHPS, 2014). Therefore, although the expressway is crucial as it creates internal integration and promotes connection in Sri Lanka, it still faced critics regarding its route choice from local communities (PILF, 2014). The opposition induced the avoidance of important elephant habitats, although the highway still passed the protected area.

Since connecting the Mattala Rajapaksa Hambantota Airport to the national expressway network is one of the main purposes of the project, a major intersection on the outskirts of Andarawewa city is selected as an additional control point for the route because it is the gateway to the airport (Fig. 2). The shortest distance (straight lines) between Matara to Andarawewa and Andarawewa to Hambantota are approximately 69.69 km and 14.53 km, respectively. Accordingly, the buffer radius used to delineate the potential route zone of our case study was 34.85 km and 7.27 km. The resulting potential route zones of the Southern Expressway Extension are shown in Fig. 2.

In the case study, the factors of "habitat connectivity", "ecological restoration priority", "cultural heritage" and "public support" were not included in the final analysis due to data unavailability. For the five factors with discrete data types in the case study (i.e. ecosystem wilderness, habitat importance, landslide susceptibility, protection status and land use suitability), resistance scores were assigned based on their categories or orders (Table S1 and S2). For the other 14 factors with continuous data, the resistance scores were classified and assigned based on the widely-used natural break (Jenks) method, which can minimize differences within a class while maximizing differences between classes (Chen et al., 2013). The details of resistance-scoring scheme for the 19 factors analyzed in the case study can be referred to Table S1 and S2. Spatial correlation analysis of the cost layers of these 19 factors showed independence of each factor in general (Table S3). We ensured the datasets used for analysis predate the start of construction of SEE whenever possible to exclude the potential influences of the actual route. For example, the year of 2015 was used as the baseline for obtaining the data of vegetation productivity, protection status, road density, nighttime light, access time to cities, population density and land cover. However, it should be acknowledged that the data of some less variable factors such as the ecosystem wilderness, endangered species richness, proximity to rivers, soil erosion suitability, etc. were not annually available and could only be obtained from best-available sources, which might lead to uncertainty in results. All data for the case study were resampled to approximately 200 m resolution to match the datasets with the finest resolution to prevent loss of information. To quantitatively compare the performance of different routing options, we also converted the least-cost path analysis results to raster data and calculated the accumulated resistance scores of each route.

For the scenario setting process, we created three scenarios based on different weights of environmental/ecological and socioeconomic factors as examples, namely balanced, environmental and socioeconomic scenarios (Table 2). The weights of each factor under different scenarios were determined by the analytic hierarchy process (AHP) method. The AHP method is an effective decision analysis tool that can quantify the

**Table 2**

Assigned weight of factors under different scenarios for the Sri Lanka Southern Expressway Extension case study.

Factors	Balanced scenario weights	Environmental scenario weights	Socioeconomic scenario weights
Ecosystem wilderness	2.870	5.077	2.870
Natural vegetation productivity	1.696	3.000	1.696
Habitat fragmentation	2.130	3.769	2.130
Habitat importance	5.174	9.154	5.174
Endangered species richness	4.435	7.846	4.435
Species rarity	4.435	7.846	4.435
Proximity to rivers	1.000	1.769	1.000
Soil erosion susceptibility	3.293	3.885	4.391
Landslide susceptibility	4.435	5.231	5.913
Protection status	15.815	∞	21.087
Total length	1.130	1.000	2.261
Slope suitability	3.696	3.269	7.391
Soil suitability	3.109	2.750	6.217
Road density	1.674	1.481	3.348
Economic activity level	4.000	3.538	8.000
Accessibility improvement potential	3.239	2.865	6.478
Population density	4.891	4.327	9.783
Land cover suitability	6.880	8.115	9.174
Virus spillover risk	2.152	2.538	2.870

relative importance of different factors on one common dependent variable, which was different development goals in this case (Sun et al., 2016; Wu et al., 2018). The factors are pairwise compared for their importance within three groups (i.e., the environmental, socioeconomic, and mixed) to the balanced, environmental and socioeconomic development priorities without making assumptions about the independence of the factors. The detailed process used in this case study can be found in the supplementary materials. Although we intended to determine the importance of each factor according to the local regulations, requirements from lending parties and reality of the case study area, the resulting weights could still be subjective and only serve as heuristic examples. We emphasize the need to adjust the weights of factors by actual stakeholders during future applications of the model.

#### 1) Balanced scenario:

After obtaining the importance of each factor within the three categories, the scenario setting process mainly focuses on determining the priorities of the factor group. Our first scenario aims to set up a planning situation that can balance both needs of socioeconomic development and environmental protection/conservation. Therefore, under the balanced scenario, we assigned equal weights to the environmental and socioeconomic groups. For the factors that can potentially cause both significant environmental and socioeconomic impacts (i.e., the mixed group), which includes the protection status, soil erosion susceptibility, landslide susceptibility, virus spillover risk and land cover suitability, higher importance were assigned to them compared to the other two groups (Table 2).

#### 2) Environmental scenario:

Under the environmental scenario, which prioritizes environmental protection and biological conservation, we raised the weights of the environmental group (including most factors of ecosystem importance,

biodiversity conservation and environmental risks) to two to increase their importance. The environmental group was assigned with higher importance compared to the socioeconomic one and matched with the importance of the mixed group. In addition, the protected areas were cut out from the potential route zone under this scenario to prevent bisecting any protected area under this scenario (Table 2).

### 3) Socioeconomic scenario

Under the socioeconomic scenario, we intended to simulate the need to find a route option that could satisfy the people who heavily prioritize socioeconomic development while minimizing the ecological and environmental impacts. Therefore, we assigned higher weights to the socioeconomic group (including most factors of economic costs, social costs and socioeconomic benefits) compared to the environmental one and raised their importance to the same level of the mixed group (Table 2).

## 3. Results

In the potential route zone of our case study, the factors of natural vegetation productivity, endangered species richness, soil erosion susceptibility, landslide susceptibility, slope suitability and soil suitability all showed a spatial pattern of higher resistance in the northwestern region and lower resistance in the southeastern region (Fig. 3). For the overall resistance, the potential route zone under the balanced, environmental and socioeconomic scenarios all showed similar spatial patterns in general (Fig. 4). The northern region of the potential route zone, especially the northwest mountainous part, displayed higher resistances than the southern region. The coastal regions had relatively lower overall resistances. The high-resistant region is more concentrated in the northwestern region under the balanced scenario but more spreading under the socioeconomic scenario (Fig. 4).

In general, the LCP results under all balanced, environmental and socioeconomic scenarios showed less meandering route choices than the

current SEE route (Fig. 5). The largest divergence among the LCP routes occurred in the section from Matara to Andarawewa (Fig. 5). In the first half of this section, the environmental LCP took a more southern route compared to the balanced and socioeconomic LCPs. The socioeconomic LCP took the most northern route among all. In the section from Andarawewa to Hambanthota, the balanced and environmental LCP routes overlapped in most areas and were located approximately one to two kilometers west toward the current SEE route. However, the socioeconomic LCP took the most western route in this section. In terms of the accumulated resistance scores of routes, the proposed LCP results under the three scenarios were all lower compared to the respective score of the current SEE route (Table 3).

For individual factors, the accumulated impacts from all LCP results and the current SEE route were calculated as the sum of unit values of the route cells (Table 3). Since factors such as landslide susceptibility, soil suitability and land use suitability were determined by multiple criteria (e.g., soil suitability was influenced by both organic matter and clay content), these factors were compared with the accumulated resistance scores among routes to identify the route option(s) that could minimize the overall negative impacts on these factors. The results showed that the Balanced LCP route among the four route options had the shortest total length (84.66 km), and avoided passing through any KBAs or protected areas in the potential route zone (Table 3). As for the Environmental LCP route, it gave better results for a total of 10 factors compare to the other three routes. Its route minimized negative impacts on ecosystem productivity, endangered species, small-ranged species, public health risks (reducing length in hotspots of species that have high pathogen spillover risks) (Table 3). Moreover, its route also passed areas with the largest potential for economic gains (accumulated nightlight value of passed area: 91.63 nanoWatts/cm<sup>2</sup>/sr), less clay- and carbon-rich soils and more urban and agricultural land use types (Table 3). For the factors of “ecosystem wilderness”, “habitat importance” and “protection status”, the Environmental LCP route was also a better choice since it avoided bisecting any wilderness areas, key biodiversity areas and protected areas (Table 3). The Socioeconomic LCP also

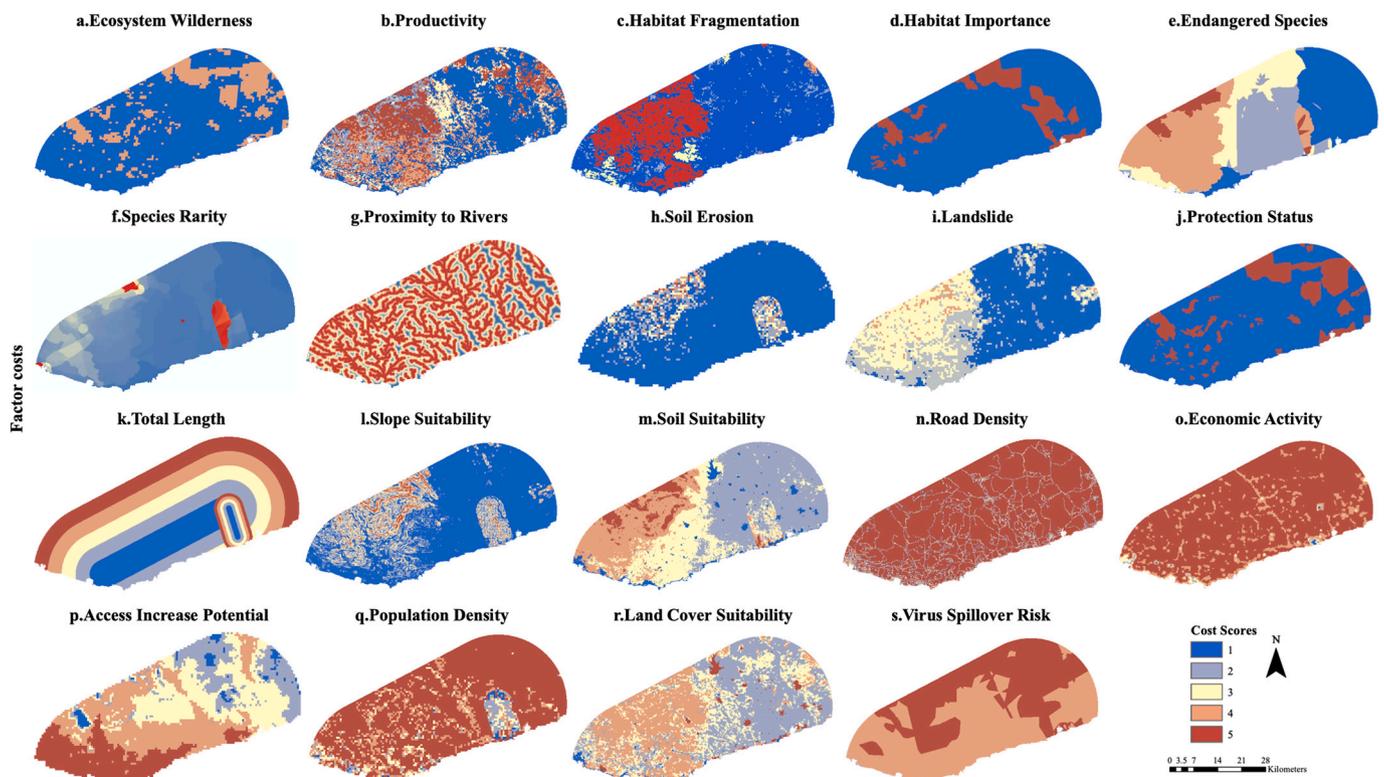


Fig. 3. Assigned resistance scores of the 19 considered factors in the potential route zone of the Sri Lanka Southern Expressway Extension project.

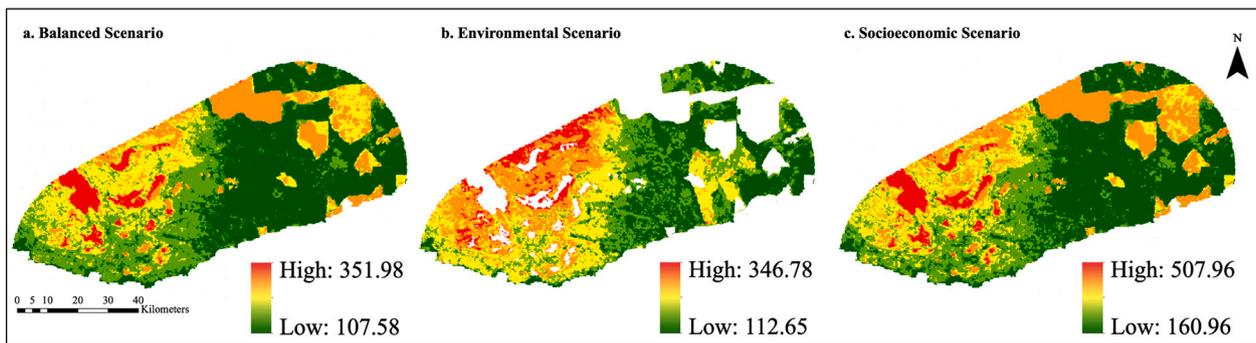


Fig. 4. Accumulated resistance maps of 19 factors under three scenarios (balanced, environmental and socioeconomic) in the potential route zone of the Sri Lanka Southern Expressway Extension case study.

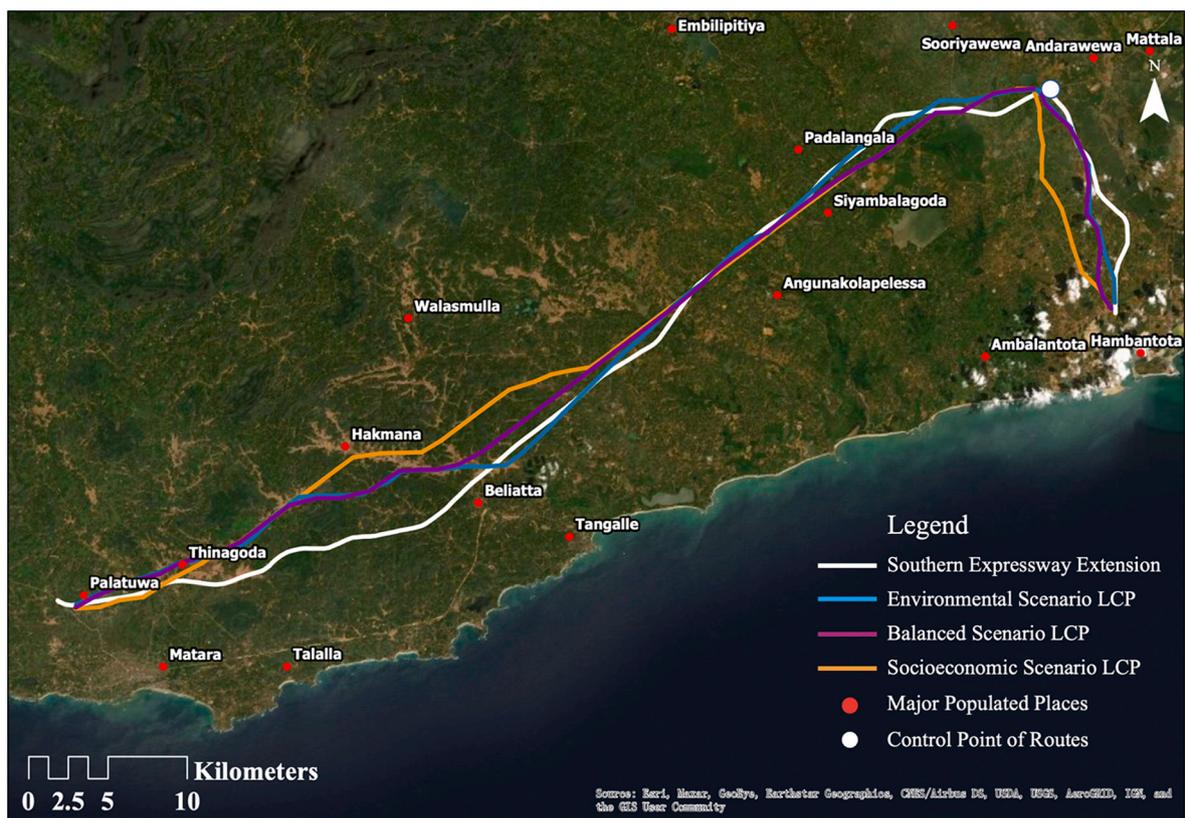


Fig. 5. Current route and least-cost path result under the balanced, environmental and socioeconomic scenarios of the Southern Expressway Extension case study in Sri Lanka from Matara to Hambanthota via Andarawewa.

avoided crossing any key biodiversity areas and protected areas. In addition, compared to the other three routes, the Socioeconomic LCP passed areas with flatter terrain, had the highest possibility of utilizing existing roads to reduce costs, the smallest impacts on habitat fragmentation, the highest terrain stability and the largest accumulated population size along the route to increase connectivity between different human residence areas (Table 3). Lastly, we also found that the current route of SEE was the best choice among the four in terms of offering the largest accessibility improvement benefits (accumulated access time to cities of passed area 17,332 min), lowest impact on aquatic ecosystems and soil erosion potential (Table 3).

#### 4. Discussion

We applied the Sustainable Linear Infrastructure Route Planning Model to generate three possible routes under different scenarios for the

Southern Expressway Extension project in Sri Lanka and compared their impacts with the current route, considering 19 different environmental, ecological, social and economic factors. In the first roughly one-third of the length from Matara to Andarawewa, the LCP results under all three scenarios chose their paths to the north of the current route to avoid bisecting the protected Dandeniya Aparakka and Kirinda Mahayaya National Reserved Forests (Fig. 5). A report by a local NGO estimated the current route of SEE cleared seven hectares of national reserve forests, which contained 137 plant species (35 endemic species, with 5 of these being endangered species and 8 being vulnerable species) (PILF, 2014). Although the habitat loss in the protected area due to current SEE construction is required to be compensated offsite (ColomboPage, 2020), it would still be more beneficial to keep the original protected area intact to reduce habitat fragmentation and potential negative impacts on biodiversity (Haddad et al., 2015; Rybicki et al., 2020).

Among the three LCP results, the Socioeconomic LCP took a shorter

**Table 3**  
Accumulated resistance scores and factor unit values of the cells of the current Southern Expression Extension route and three least-cost path analysis results.

Scenarios and factors (unit)	Southern Expressway Extension	Balanced least-cost path	Environmental least-cost path	Socioeconomic least-cost path
Balanced Scenario	94,221	88,192	–	–
Environmental Scenario	101,822	–	95,710	–
Socioeconomic Scenario	147,970	–	–	138,819
Ecosystem wilderness (km of routes in wild areas)	7.80	0.40	<b>0.20</b>	3.20
Vegetation productivity (kg C/m <sup>2</sup> )	181.48	135.22	<b>122.42</b>	161.38
Habitat fragmentation (average km <sup>2</sup> of passed forest patches)	3407.63	3007.76	3469.25	<b>1322.86</b>
Habitat importance (km of routes in KBA)	2.60	<b>0</b>	<b>0</b>	<b>0</b>
Endangered species richness (accumulated no./km <sup>2</sup> )	14,876	14,607	<b>14,574</b>	15,258
Species rarity (rarity score)	2.40	2.39	<b>2.38</b>	2.49
River proximity (m)	<b>525,865</b>	405,182	427,835	357,733
Soil erosion susceptibility (t/yr)	<b>41,724</b>	60,957	55,677	90,050
Landslide susceptibility (resistance scores)	852	825	812	<b>796</b>
Protection status (km of routes in PA)	1.80	<b>0</b>	<b>0</b>	<b>0</b>
Total length (km)	96.00	<b>84.66</b>	86.44	85.73
Slope suitability (degrees)	738.75	753.77	782.64	<b>717.42</b>
Soil suitability (resistance scores)	1414	1338	<b>1308</b>	1342
Road density (m)	407,553	531,427	506,602	<b>573,986</b>
Economic activity (nanoWatts/cm <sup>2</sup> /sr)	67.20	80.54	<b>91.63</b>	69.21
Accessibility improvement potential (min)	<b>17,332</b>	16,584	16,527	16,582
Population density (population size)	222,814	234,955	255,549	<b>320,322</b>
Land use suitability (resistance scores)	1466	1335	<b>1269</b>	1350
Virus spillover risk (accumulated no./km <sup>2</sup> )	31,775	30,460	<b>30,301</b>	30,424

Bold values indicate the corresponding route is the best choice for optimizing the impacts on the factor.

route from Matara to the control point in Andarawewa, which pushed it toward the north. Furthermore, the town of Hakmana, which is located to the north of the current SEE route, is also now connected by the Socioeconomic LCP. In the second section from Andarawewa to Hambanthota, the three LCPs all shifted toward the southwest compared to the current SEE route. The shifts were mainly the results of joint influences from the higher slope suitability, lower landslide susceptibility and relatively shorter length in the southwestern part of this section (Fig. 3). The Socioeconomic LCP was particularly drawn toward the southwest due to the higher population density in the region (Fig. 3). In addition, we also found that the current SEE took the advantage of a pre-existing tertiary road to minimize construction costs by examining the historic road map of Sri Lanka (Geofabrik 2021). Although the possibility of using existing roads should be a considering factor in route planning (e.g. the road density factor in our model aims to assess the possibility), we believe that potentially better route options might be identified by simultaneously considering various other factors such as the ones used in the model.

For future applications, our proposed route planning model can be easily incorporated with the current SEA process, which implies its application would be in the pre-implementation phase and focus on a relatively broad spatial scale. Therefore, it is important to keep in mind that the exact location of linear infrastructure still requires information on site scale factors, such as the function of roads or railways, microclimate, land tenures and economic feasibility, and further Environmental Impact Assessment validation before actual construction. (Jaeger, 2015; Stokes, 2015). Compared to the factors used in Laurance et al. (2014)'s global road strategy, we included all aspects they considered but paid relatively less attention to the importance of agricultural production; instead, a wider range of socioeconomic benefits and costs were covered in our proposed model (Laurance et al., 2014). We believe the importance of these added socioeconomic factors could become more prominent at the landscape and regional scale compared to the global one (Mahamid, 2011; Tijić et al., 2020). This tool is designed for multiple target users, including policy makers, construction company, project lending institutions such as multilateral banks and Chinese banks and local communities. For example, banking system may use it as a tool to support green financing along Belt and Road Initiative countries. With the help of more and more accessible data sources and methods, such as the UN Biodiversity Lab platform for sustainable development supporting data, the National Earth System Science Data Center of China for extensive BRI-related data and the participatory decision making process, the target users can acquire the data needed for the model more easily and customize a list of considering factors.

In addition, it should also be kept in mind that the factor weights under different scenarios are flexible and should be determined by all possible stakeholders in future applications. With the growing numbers of linear infrastructure projects in BRI countries across the globe, potential conflicts among project host countries, local communities and lending institutions could increase since they might have diverse socioeconomic goals and environmental requirements (Losos et al., 2019; OLGPBRI, 2019). Our proposed model offers the possibility and encourages stakeholders to resolve potential conflicts by using the scenario setting process to test route options under various priorities. Finally, it is worthy to note that different linear infrastructure types, such as railways, limited-access highways and conventional roads, might differ in their abilities to affect environmental and socioeconomic factors (Losos et al., 2019). Therefore, they might need to be treated differently after the route planning stage. For example, conventional roads might need more mitigation actions (e.g. avoid, reduce, restore, offset) during construction than railways to reduce environmental impacts because their impacts could be more extensive and spreading (Losos et al., 2019). However, since most linear infrastructure types share similar socioeconomic goals (e.g. connecting people, markets) and environmental/ecological concerns (e.g. causing habitat loss, fragmentation), our proposed model should apply to all of them during their route planning

stages.

In summary, to minimize the environmental/ecological impacts while maximizing the socioeconomic benefits of roads, highways and railways, we proposed a comprehensive Sustainable Linear Infrastructure Route Planning Model, which consists of a total of 23 environmental, ecological, social and economic factors. These factors in combination with different scenario setups may offer stakeholders a flexible and potentially participatory decision-making tool to identify more sustainable route options for linear infrastructure projects. The proposed model can be easily incorporated with the Strategic Environmental Assessment process to improve the spatial sensitivity of impact evaluation. The case study of the Southern Expressway Extension project in Sri Lanka demonstrated the validity of the model. In future applications, the proposed planning model should also be in company with more environment-friendly construction technology, constant monitoring and thorough management policies (such as no-net-loss strategy) to further improve the sustainability of linear infrastructures. Although this model can help to identify the alternative and more sustainable route both environmentally and economically. To protect certain species, stakeholders should compare the current planning with the alternatives, and thus decide whether to use the alternative to avoid an area or stick with the current planning but build wildlife crossings to mitigate the impact. The costs and effectiveness of the wildlife crossings need to be further examined. Last but not least, we also want to point out the future possibility of applying the general framework of the model (i.e., planning zone delineation, factor selection and resistance score assignment, scenario setting and least-cost path analysis) on the spatial planning of infrastructures beyond roads and railways, such as real estate, power plants, etc. Suitable factors can be identified to assess a wide range of potential impacts of these projects spatially. These factors need to enable planners to answer key questions like where should or should not to locate a potential infrastructure

#### CRedit authorship contribution statement

**Shuyao Wu:** Methodology, Data curation, Visualization, Investigation, Writing- Original draft preparation.

**Binbin V. Li:** Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing.

#### Declaration of competing interest

No conflict of interest exists in the submission of this manuscript.

#### Acknowledgments

We thank the National Natural Science Foundation of China (31800394) to fund this research.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biocon.2022.109449>.

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