Technological Forecasting & Social Change 215 (2025) 124068

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

Hidden structures of a global infrastructure: Expansion factors of the subsea data cable network

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A R T I C L E I N F O

Keywords:
Submarine data cable
Subsea data cable
Internet backbone infrastructure
Critical infrastructure
Maritime infrastructure
Internet access

A B S T R A C T

The network of subsea data cables (SDC) transmits the majority of international and intercontinental data exchanges. After thirty years of fiber-optic SDC installation across the oceans, almost all coastal and island countries gained access to the only global fixed infrastructure network. Still, there is considerable inequality in the number of available SDC accesses, creating deficits in redundancy for less connected states. Previous research hypothesized multiple factors that influenced the build-up of internet infrastructures but failed to verify these assumptions through inferential statistics. This work highlights the national-level factors that made backbone access provision more – or less – attractive to SDC project decision-makers. Our regression analysis of global country-year data (n = 4916) found that socio-economic (population, GDP), political (state fragility, conflict), and geographic factors (seismic hazard, neighboring territories) significantly influenced the number of active and planned accesses. This work can serve as a foundation for further research leveraging quantitative statistics to unveil hidden structures in the construction of material internet infrastructures and support sustainability in the future allocation of international infrastructure development resources in general.

1. Introduction

Data can be considered the central resource in digitized societies of the 21st century. Currently, access to and transmission of data is primarily provided via the internet, which, therefore, plays a crucial role in the development of states. For example, business transactions, private calls, and military communication mainly depend on the internet (Davenport, 2015). However, 2.6 billion people – 68 % of the world's population – do not yet use the internet (International Telecommunication Union, 2024). The lack of access to physical internet infrastructures contributes to this condition (Oughton, 2023). Most current research considers internet connectivity as a given, inexhaustible resource, while the physical infrastructures that provide the internet remain insufficiently researched. Fiber-optic subsea data cables (SDC[2]) currently provide about 99 % of intercontinental data traffic. Over 550 active SDC form bottlenecks for international telecommunication, bundling data from the extensive land-based networks of terrestrial data cables (TDC) for intercontinental transmission (International Telecommunication Union, 2021). These properties make them a central asset of digitization processes and critical infrastructure (CI) in the sense of most national and international definitions (Fraunhofer IAIS, 2019; Kavanagh et al., 2025). As the most extensive fixed infrastructure network of present times – and the only one interconnecting all inhabited continents – the expansion of SDCs and its factors may inform the analyses and foresight on future maritime structures. In particular, the energy transition will make it necessary to expand electric energy networks over longer distances and across seas. The European Union's plan to fund a hybrid energy and telecommunications cable across the Black Sea, connecting Georgia, serves as a prominent example of what has been termed "cable diplomacy" by Bueger et al. (2022). This approach is gaining traction within EU policies, as evidenced by its incorporation into the Cable Projects of European Interest (CPEI) funding framework proposed by the European Union (European Commission, 2024, 2025).

The expansion of SDC has not been a globally balanced process

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[2] List of abbreviations:CI = critical infrastructure, CLS = cable landing stations, DV = dependent variable, GDP = gross domestic product, ICT = Information and Communication Technology, IV = independent variable, TDC = terrestrial data cables, MSP = marine spatial planning, SDC = subsea data cables, VIF = variance inflation factor.

https://doi.org/10.1016/j.techfore.2025.124068
Received 22 May 2023; Received in revised form 14 January 2025; Accepted 19 February 2025

(Fouchard, 2016; Schwartz and Hayes, 2008; Thorat, 2019). Rather, to date, some states and territories have little or no connectivity to the high-capacity network, while others have numerous access points (Cariolle, 2019; Franken et al., 2022; Omer et al., 2009; Thorat, 2019). Complex considerations underlie the decisions determining the year of connection and the routing of SDC projects, which usually cost hundreds of millions of USD. The construction cost of an international SDC depends on several factors, most notably on length, the number of cable landing stations (CLS) installed, the planned bandwidth, and geographic location (Agrawal, 2016). Telecommunication companies generate profit from SDC transmission contracts that must pay off the construction and operation investments over time. Large content providers that entered the SDC market about 10 years ago, must as well look for proximity to their users and availability of data center and energy infrastructures. Accordingly, SDC connections are economically attractive if a large customer or user base coincides with existing regional infrastructure and an assumed unsatisfied demand for internet capacity.

However, we presume that several factors, in addition to commercial-economic motives, have influenced the expansion of the SDC network. While economic viability and customer potential certainly play a central role, there are some puzzling cases whose late or lacking connection to the internet backbone base is conspicuous. For example, Eritrea has no CLS and thus no direct access to the SDC backbone, despite its proximity to twelve active SDC systems in the Red Sea (see Fig. 1). This should be seen against the background that Eritrea only gained independence from Ethiopia in 1991. After a two-year war beginning in 1998 that resulted in 100,000 fatalities, a peace treaty was signed in 2018. All other Red Sea littoral states have been connected to SDC for many years.[3] Additionally, all planned major projects that will provide more connectivity for other African countries in the future (Africa-1, 2Africa, SEA-ME-WE-6, Raman, IEX) avoid Eritrea, although the SDC branches required would not exceed 20 km. This lack of direct access is remarkable as Eritrea's population of 6.1 million only indirectly supplied by transit networks through Djibouti or Sudan. On the other side of the spectrum of connectivity lie the US, with over 65 active international SDCs connecting its territory and 14 new cable systems planned until 2028.

We aim to relate the different timing and diversity of international SDC connections to the economic, geographic, and political context in which telecommunication companies decided to build an SDC to answer this puzzle. Our scope of investigation covers the entire maritime part of the material internet infrastructure, aiming to include all coastal and island territories that can link to the SDC network. Furthermore, we intend to analyze the factors promoting or hindering the likelihood of SDC access by including geographic, political, and socio-economic variables. The analysis is limited to SDC projects from the beginning of the fiber-optic technological turn in the internet industry (1995) to the current-day SDC projects (2025) (Submarine Telecoms Forum, 2022; Zsakany et al., 1995) leading to the research question: ***What socio-economic, political, and geographical factors influenced the number of international subsea data cables accesses per territory between 1995 and 2025?***

The main goal of this work is to introduce a set of new factors not yet analyzed through quantitative methods in relation to the SDC networks before – the geographic and political factors. The socio-economic factors we apply for the analysis (population and economic performance) are well established in research, and time will serve as a control variable.

2. Related work and research gap

In our view, the global SDC network must be understood as a complex, constantly changing socio-technical infrastructure (Lovell et al., 2022). Approaching material internet infrastructures as the product of decades of development, installation, and technological sedimentation is needed. Two aspects that have received little attention so far are the decision-making stages of the transit network deployment and the social contextualization of SDCs (Starosielski, 2015). Also, Bueger and Liebetrau (2021) argued that, despite their central role in today's private, governmental, and economic activities, SDCs were inadequately recognized in research and society at large. The researchers identified a "triple invisibility" inherent in SDC's characteristics as (1) buried, (2) maritime infrastructures (3) widely taken for granted. Furthermore, they identified a tendency for the current scholarship to split into fundamentally different meta-narratives closely linked to individual disciplines and their respective epistemologies. Two discourses are relevant to this work, the one within the technical and industry realm and the other within the wider social sciences and policy field.

2.1. Technical and industry discourse

Within the technical disciplines, the general discourse on SDCs focuses on technological advancements or the ideal routing of an SDC project based on economic viability, natural hazards, or the regularity of accidents (Mauldin, 2017; Xie et al., 2019; Yincan et al., 2018). These approaches work with market research and desk study methods, i.e., the preparatory examination of an SDC project based on bathymetry, seafloor characteristics, and current geo-data. Some studies deal with resilient planning of a network, primarily focusing on routing decisions for accident prevention (Paximadis and Papapavlou, 2021; Wang et al., 2019b) and redundancies for failure prevention (Anonymized Authors, 2022). Another focus is the avoidance of areas vulnerable to geological and human influences (Wang et al., 2019a; Xie et al., 2019). A comparably recent body of literature addresses SDC in the context of marine spatial planning (MSP) beyond territorial waters, where fixed infrastructures compete with other uses of the seabed, such as fishing, energy infrastructures, and mining (Altvater et al., 2019; Friedman, 2019). In general, works in this area are practically aligned with and sometimes funded by the SDC industry for their tangible operational value.

In the technical literature stream, economic and socio-economic factors dominate in terms of explications for the ways of the internet's expansion (see Table 1). Still, the analyses are mainly from the present-day perspectives of the respective publications (Cariolle, 2019; Anonymized Authors, 2022; Omer et al., 2009; Palmer-Felgate et al., 2013; Palmer-Felgate and Booi, 2016; Ross, 2014). These quantitative works on the internet's expansion already hint at the central role of economic factors. For the SDC industry, Gjesvik (2023) identified two phases of varying economic driving forces. Before 2010, telecommunication companies sought the "safest return on investment" (Gjesvik, 2023, p. 732) and, therefore, connected metropolitan centers that offered a large, well-connected and established customer base as well as "terrestrial networks able to transmit large amounts of traffic, internet exchanges for transferring data between networks, and secondary infrastructures like electricity and a trained workforce to ensure a smooth operation" (Gjesvik, 2023, p. 732). Therefore, markers like population, population density, and varying measures of economic performance are regularly applied in quantitative works explicating the internet's expansion. Centralization effects in the ownership of the material internet, as predicted by Wu (2010), are increasingly hypothesized. With the arrival of hyperscalers (Meta, Google, Amazon, Microsoft) activity in the SDC market, the industries' focus on economic drivers shifted over time toward Cloud Service Providers' needs and preferences, which include the close connectivity of SDC with their global data centers. These data centers require enormous amounts of power for cooling, which makes locations with colder weather economically more attractive.

[3] Israel in 1994, Saudi Arabia and Egypt in 1997, Djibouti in 1999, Sudan in 2003, Yemen and Jordan in 2006.

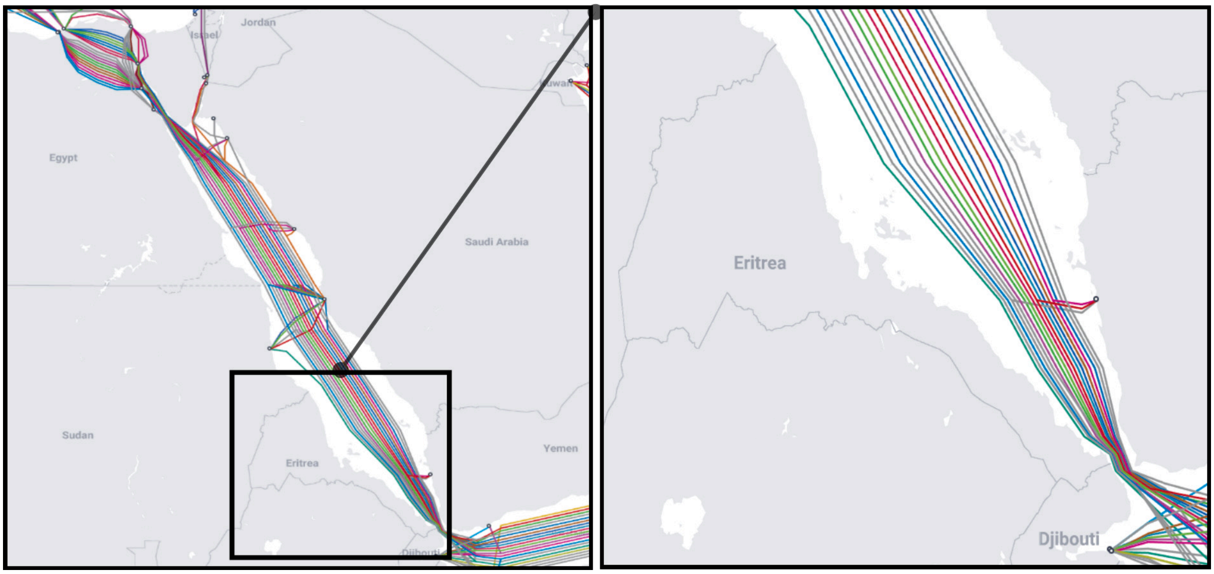

Fig. 1. The Eritrean Puzzle: Despite being close to many subsea cable systems and its potential customer count of six million citizens, Eritrea has no direct SDC link. Solid lines show active SDC systems, and dashed lines indicate projects under construction (Map details taken from TeleGeography, 2024).

Table 1
Selection of quantitative studies regarding influencing factors of global internet diffusion in general. Significant factors (0.05 threshold) are marked if a positive ("+") or negative ("–") correlation was found. Insignificant or inconclusive findings are marked with "°".

Study	Time scale	Unit selection	Method	Dependent variable	Factors
Chinn and Fairlie, 2004	1999–2001	161 countries	Multiple linear regression analysis	Computer use rate	Phone costs°, electric power consumption+, age average°, urban population+, trade/GDP+, education level°, rule of law°
Guillén and Suárez, 2005	1997–2001	Sample of 118 countries	Multiple linear regression analysis	Share of internet users	World-system status (core+/periphery–), privatization of telecommunication+, democracy+, cosmopolitanism+, GDP+, phone costs°
Andrés et al., 2010	1990–2004	214 countries	Multiple linear regression analysis	Share of internet users (time-lagged)	GNI per capita (p.c.)+, Market competition: number of providers+, phone costs–, phone lines per capita+, computers per capita+
Doong and Ho, 2012	2000–2008	136 countries	Cluster analysis	ICT development (cluster scores)	Wealth (GNI)+, spatial proximity of countries+
Ross, 2014	1989–2013	115 countries & substate entities	Network analysis & multiple linear regression analysis	Diversity of CLS per country	Coastline length°, early backbone membership°, degree centrality°, betweenness centrality+, military spending°, GDP per capita°, state stability°, political rights°
This work	1995–2025	175 island and coastal territories	Multiple linear regression analysis	SDC backbone connection(s)	Socio-economic, political, and geographic factors

2.2. Social sciences and policy discourse

Gjesvik (2023) also identified potential political factors leading to the second discourse. Aspects increasingly discussed are regulatory and fiscal factors, which may hinder the industry's perceived attractiveness of an SDC landing location. For example, critical infrastructure regulations (obligatory protection measures, incident reporting duties), environmental protection regulations leading to prolonged permitting and licensing processes, and tax levels vary widely across states. Privacy or surveillance-driven data localization regulations or access point reduction is hypothesized to impact terrestrial internet infrastructures and the SDC network (Ross, 2014; Sargsyan, 2016).

In security studies, SDC and other maritime infrastructures are interpreted as attack vectors for hostile state and non-state actors. In this context, the SDC network is analyzed as a potential target of malicious actors (Martinage, 2015; Shvets, 2021). The respective discourse displays a certain tendency toward securitization (Buzan et al., 1998), sometimes recommending the militarization of SDC protection (Ross, 2014; Burdette, 2021). Correspondingly, the geopolitics-inspired literature features neorealist approaches that focus on the SDC network as a potentially threatened military or dual-use resource in the wake of geopolitical competition (Baezner, 2019; Morel, 2022; Sherman, 2021). Especially for the Indo-Pacific region, research suggests that Chinese, Australian, US, and European public (co-)funding in cable infrastructures is used as a political tool to bind smaller nations toward the sponsoring nation (Hamel, 2024). At the same time, SDCs themselves can be an instrument of weaponization. However, as Gjesvik (2023) nuances out, the potential of weaponization of infrastructure networks by states depends on their privileged positions, which in turn are constantly renegotiated with private corporations growing power and agency.

Geographic factors underly both discourses. The technological and industry discourse uses micro- and meso-level geographic data to include outage prevention in route planning. The geopolitics discourse focuses more on the global reach and the countries' situations. For example, the works applying inferential statistics to various areas of internet diffusion in Table 1 used factors like spatial proximity of countries, core/periphery measures and coastline length to measure the geographic situation. Hamel's work on Pacific island nations also suggests that the insular situation may play a role (2024).

2.3. Research gap

The current scholarship on SDCs reflects a dichotomy between technical and social science discourses. While technical studies emphasize economic and geographic factors, such as market demand and routing feasibility, they often overlook the broader political, regulatory, and contextual dimensions. Conversely, social science approaches explore regulatory challenges and geopolitical situations but rarely test these hypotheses quantitatively. This separation leaves a critical gap: the lack of a comprehensive framework that integrates and tests multidimensional influences on the global SDC build-up. Few works quantitatively examine the combined impact of technical, economic, political, and geographic factors. For example, "laws of attraction" and "logic of avoidance" (Starosielski, 2018) have been proposed, but they remain untested by quantitative means. This study addresses the research gap by bridging the two discourses through a multifactorial analysis. Other works have done similar approaches, but either with a different scope, such as Flensburg and Lai's (2020, 2021) works on the Danish internet infrastructure or exploring broader topics of internet penetration and diffusion (see Table 1). Our contributions are twofold: First, expanding the technical discourse to incorporate a broader set of political and geographic factors and applying its findings on a global scale. Second, the hypotheses selected from social science literature will be tested using quantitative methods. By doing so, this research advances an integrated understanding of the driving and hindering factors in SDC deployment.

3. Hypotheses

In theory, there is a broad choice of potential hypotheses for factors of the SDC expansion available, ranging from the route characteristics of SDC, properties of SDC, or those of their landing points. Instead, we chose the national connectivity perspective to enable analysis on a global scale with country-years as the unit of observation. The following hypotheses were selected with data availability in mind, aiming to include as many coastal territories as possible.

3.1. Socio-economic factors

As most SDC projects are pursued and owned by private, for-profit entities, economic factors often serve as the foundational arguments for explaining communication network structures. According to the digital divide research, internet infrastructure is unevenly distributed globally and skewed toward wealthy countries (Doong and Ho, 2012; Guillén and Suárez, 2005; Pick and Nishida, 2015). Furthermore, the divide is considered immense, so income levels in low-income countries are of greater importance to internet adoption or extension than in high-income countries (Andrés et al., 2010). The tertiary sector is highly dependent on the broad availability of connectivity, not only for the provision of services but also for the accessibility by customers. We propose the corresponding hypothesis:

Hypothesis (H)1. *Higher socio-economic performance raises the number of available SDC access routes.*

A large population means a more extensive potential customer and user base, so territories with a larger population may attract more and faster SDC build-up (Park et al., 2015; Robison and Crenshaw, 2010). Also, installations of SDCs often require costly licensing procedures in all adjacent countries. A more extensive customer and user base then raises the cost-efficiency of an SDC project. Therefore, we presume:

H2. *Greater population correlates with more SDC access routes.*

The above hypotheses on socio-economic factors mirror mainstream factors established in research on SDC. However, to overcome the notion of economic motivation mainly in SDC construction, we will formulate hypotheses to include political factors that may also play a role in decision-making processes.

3.2. Political factors

Various political factors are discussed in research. For example, Guillen and Suarez identified a positive link between democracy and the internet users share as early as 2003. In the meantime, the internet as a mass communication medium was immensely leveraged by authoritarian states for their benefit at the same time (Rød and Weidmann, 2015). Therefore, we refrained from including a measure of democracy in the final model. Much more, state fragility may influence the SDC network build-up. Fragility comprises factors like internal disputes and challenges to a government in the broader sense (social grievances, resource inequalities, recurring conflicts). The concept of state fragility emerged from the research on failed and failing states, creating a continuous scale from the formerly three-stage concept (Fund for Peace, 2021; Grävingholt et al., 2015). State fragility leads to insecurity about government efficiency, lower economic capacity, and emigration movements. Vice versa, stable state institutions can provide more incentives for private companies to invest in infrastructure projects securely, have reliable regulations in place, and exert more political control over the national labor market (Gjesvik, 2023; Ross, 2014). All those aspects speak in favor of a negative link of fragility to SDC access:

H3. *State fragility is negatively related to the number of SDC access routes.*

Violent conflicts damage cable infrastructures and threaten the function of communication systems in general. Recently, a merchant vessel targeted by Houthi rebels drifted crewless, severing multiple cables in the Red Sea. The MV Rubymar incident shows the long-term consequences of conflicts in deterring cable repair and build-up to countries in conflict (Bashfield, 2024). Also, areas of violent conflicts are more prone to internet outages, making them less attractive for economic use (Gohdes, 2015). Therefore, we propose:

H4. *The occurrence of violent conflicts is negatively related to the number of SDC access routes.*

3.3. Geographic factors

Geographic location determines a territory's context and neighborhood and can potentially influence the quality of access to the global internet infrastructure (Starosielski, 2015). The most common geographic differentiation of territories is their insular, coastal, or landlocked position. While islands can receive high-capacity broadband internet access exclusively through SDC, landlocked countries must resort exclusively to terrestrial links. Either technology can connect coastal states. Due to these different prerequisites, we propose that:

H5. *A higher number of neighboring countries negatively influences the number of SDC access routes.*

Also, the geographic location of territories determines their exposure to natural hazards. For example, earth- and seaquakes, storms, tsunamis, volcanic eruptions, and turbidity currents harm SDC systems, making their routing, installment, and maintenance more costly (Pope et al., 2017). Seismic hazards, in particular, frequently cause outages of subsea cables. Gjesvik stated that "the absence of earthquakes, floods, and other natural hazards are […] significant factors" (Gjesvik, 2023) for the attractiveness of data center locations, which may, in turn, attract SDCs. Conversely, by planning redundant routes, communication providers may prepare territories with an increased risk of downtime due to seismic hazards. Large-scale simultaneous SDC faults following seaquakes and turbidity currents, such as the incidents off Taiwan in 2006, Japan in 2011, and Côte d'Ivoire in 2024, may have supported the awareness (Cho et al., 2011; Kazama and Noda, 2012). We hypothesize that industrial players perceive the need for more connections to territories characterized by more seismic activity (Eidsvig et al., 2017):

H6. *Greater exposure to seismic hazard increases the number of SDC access routes.*

With these hypotheses on the global SDC network's build-up at hand, we next introduce the statistical method and operationalize the above factors.

4. Method

This section presents the quantitative method selected to test the hypotheses related to the factors influencing international subsea cable projects. The first part details the use of linear regression analysis as a statistical model to identify correlations between the selected variables. This approach is particularly advantageous as it allows for a global perspective, enabling a comprehensive analysis across different countries and regions. Additionally, it facilitates hypothesis testing to validate prevailing opinions, particularly in the socio-economic domain, while also examining the influence of political and geographical factors, which may have been underexplored in previous studies.

The second part covers the operationalization of these factors, with a focus on the availability of country-year-coded datasets for each measure. By leveraging this data, the analysis can systematically assess the relative importance of each factor, providing a balanced understanding of the dynamics at play. This method is well-suited to address the identified research gap, offering robust insights into the interplay between economic, political, and geographical influences on international subsea cable projects.

4.1. Multiple regression analysis

Regression analysis is probably the most common statistical modeling method to analyze numerical data correlations. Multiple linear regression is an inferential statistical method that explains an observed dependent variable (DV) by multiple independent variables (IVs). The OLS model is linear in its parameters, with the DV y being a function of the IVs x_k. K reflects the number of variables included, t the number of observations, and β_k the standardized regression coefficients. The regression equation is completed by an error term ε_t that indicates the residuals.

$$y_t = x_{t1}\beta_1 + x_{t2}\beta_2 + \cdots + x_{tK}\beta_K + \varepsilon_t \quad (1)$$

The dependent variables being positive integers leaves the linear regression as the method of choice for modeling the hypothesized multiple factors for the SDC build-up. We performed the statistical calculation (OLS method) and subsequent checks in *R*. For enhanced visualizations, the package *ggplot2* was used (Wickham, 2016).

However, when dealing with outliers or violations of the assumptions of homoscedasticity, normality, or linearity, the OLS method might produce biased estimates. In such cases, robust regression offers an alternative that mitigates the influence of outliers and provides more reliable estimates. The robust regression modifies the estimation process to reduce the weight of outliers, often using methods such as M-estimators, Huber weights, or Tukey's biweight.

The robust regression equation is similar to the OLS regression but includes a robustness weight w_t that adjusts the contribution of each observation based on its residual:

$$y_t = w_t(x_{t1}\beta_1 + x_{t2}\beta_2 + \cdots + x_{tK}\beta_K) + \varepsilon_t \quad (2)$$

where w_t is the weight applied to each observation t, typically based on the size of the residuals ε_t. These weights help in minimizing the influence of outliers, leading to a more reliable estimation of the regression coefficients β_k. Robust regression, performed using robust estimation methods in R, offers a complementary approach to OLS, particularly in datasets where outliers or heteroscedasticity may impact the accuracy of the standard linear regression model.

4.2. Operationalization and data availability

This subsection introduces the various variables used in the models, beginning with two DVs. The independent variables are grouped into socio-economic, political, and geographic clusters of factors.

4.2.1. Dependent variable: SDC accesses

The dependent variable uses the cumulative value of *active and planned SDC* available to a country in the given year to approach the research question. It mirrors the general, long-term factors that help explain the structure of the backbone network.

A country-year scope is a standard unit for analyzing international phenomena that span multiple years or decades. We constructed the DV based on the dataset used by Anonymized Authors (2022) but further expanded it to include international SDC systems that were already set out-of-order or not yet planned on the cut-off date (06/2020) of the analysis. Whereas past works on the SDC usually rely on only one database, Anonymized Authors (2022) gathered information from multiple sources to obtain a wide range of data and cross-validate the info. For this, they synthesized publicly available information from numerous SDC data sets:

Submarine Telecoms Forum's *Submarine Cable Almanac* provides a quarterly global insight into active SDC routes (n = 422) (Submarine Telecoms Forum, 2022). The TeleGeography's *Submarine Cable Map* offers even more detailed data (n = 480) (TeleGeography, 2022). Similarly, Infrapedia's *Infrastructure Map* shows detailed SDC capacity data submitted by experts and is constantly validated (Infrapedia, 2021). In the rare cases of conflicting information on the CLS of an SDC, Anonymized Authors chose the information from the *Submarine Cable Almanac* to prevent potential entry errors of the *Infrastructure Map*, which has only been in operation since 2019.

However, we excluded two types of SDC from the dataset. First, multi-use energy and communications cable systems provide internet to fixed maritime infrastructure, mostly drilling platforms (Submarine Telecoms Forum, 2022). Therefore, only cables with intended onshore internet provision to countries are included. Second, only SDC-providing international connections are considered in the analysis, as these are the relevant backbone access points. Domestic SDC networks are usually installed by regional Tier-2 providers and underly different motivations. Also, multiple CLSs of the same SDC system in one country did not count as additional accesses.

The research question is aimed at decision-making factors for SDC construction. However, the process from initial decisions and plans to install an SDC to the ready-for-service date takes five years on average. Therefore, the dependent variable (*DV*) of cumulated SDC accesses at a given country-year has been time-lagged five years in the past because it mirrors the foreseeable state of the network, as planned competing projects are usually known to SDC project decision-makers.

4.2.2. Operationalizations of socio-economic factors

The first variable to measure socio-economic performance (*H1*) is the Gross Domestic Product (GDP). Although not without critique (Aitken, 2019; Costanza et al., 2009), the GDP is one of the most common measures of the wealth of states and state-like entities. The World Bank's *DataBank* provides country-year panel data for multiple measures of GDP (World Bank, 2022). We chose the GDP per capita (*GDPpC*), oriented at the 2015 USD, to measure socio-economic performance. The headcount considers the varying populations of territories listed in the World Bank data. For cross-checking, we also included the GDP (2015 USD), its logarithm (log),[4] and the Human Development Index in the data set (Roser, 2014).

[4] Logarithmic functions can be used to prevent few cases with extreme values (outliers) from influencing a statistic model too strongly, overshadowing the general trend. For example, the USA and China are outliers in terms of GDP.

The population (H2) per country-year is taken from the DataBank data set (World Bank, 2022) and processed through a log function (*logPopulation*) to prevent outlier overestimation – in this case, China and India. We considered only including the population over the age of fifteen to model potential customer bases. However, as SDCs are operated for 25 years on average, and internet usage is skewed toward youth in all world regions (International Telecommunication Union, 2024), the SDC industry should perceive young populations as future customers. Therefore, we kept the total population count as operationalization.

4.2.3. Operationalizations of political factors

To model the broad concept of state *fragility* (H3), we resort to the fragile state index (FSI) of the Fund for Peace (2021). It measures all UN members except for 15 territories omitted due to data scarcity.[5] The index results from quantitative, qualitative, and content analysis moderated at the Fund for Peace and takes values between sustainable (0) and alerting (120) estimates of fragility. We divided the 0–120 scale into 12 groups, each in increments of ten. When data were missing, we used the closest data point available for the country-year.

Data for the operationalization of *conflict (H4)* was taken from the UCDP/PRIO Armed Conflict Dataset (Davies et al., 2024; Gleditsch et al., 2002). This conflict-year dataset holds information about armed conflict where at least one party is the government of a state in the time period 1946–2023. The binary variable *conflict* considers 25 or more battle-related deaths per country-year a conflict.

4.2.4. Operationalizations of geographic factors

Neighbors (H5) were operationalized as an integer representing the number of countries that share a border with a given country.

Data from the Global Seismic Hazard Map 2023 was used to model a country's vulnerability to *seismic hazards (H6)* (Johnson et al., 2023). The map illustrates the geographic distribution of Peak Ground Acceleration (PGA) in units of *g* on rock conditions with a 10 % probability of being exceeded in the next 50 years. The PGA scale ranges from 0.00 to 1.50, divided into twelve intervals, which were also incorporated into the model. For each country-year, the location tile of the cable landing with the most adjacent cables was used. To cross-check the data, we also included the minimal and maximal seismic hazard category of a territory's tiles in coastal situation.

4.3. Time as control variable

The temporal dimension certainly plays a role in the expansion of the global internet. In times of exponential data demand growth, SDCs are planned with a design capacity to serve economically for up to 25 years. This means that over time, SDCs accumulate in territories as long as the construction of new cables surpasses the number of retired cables, which can be presumed as the regular case. For our analysis over 3, time will be included in the regression through the year of the observation to control for this effect.

5. Analysis and results

In this section, we merge the variables into multiple regression models to determine if the IVs have an explanatory value for the DV. Afterward, we give an overview of the results for the socio-economic, political, and geographic factors. The section closes with the post-tests.

[5] Including the coastal and island units of Dominica, Kiribati, Marshall Islands, Monaco, Nauru, Palau, St. Kitts & Nevis, St. Lucia, St. Vincent & the Grenadines, Tonga, Tuvalu, and Vanuatu.

5.1. Regression results

We constructed regression models for the *DV* (see Table 2). For Model 1, we selected the variables GDP, logPopulation, State Fragility, Conflict, Seismic Hazard, and Neighbors as IVs. The Adjusted R^2 score of 0.4315 and significance at the 0.001 level in Model 1 speak for its medium-high predictive capacities. Further reduction of variables did not lead to higher R^2 values. The *DV* proves to be linked to factors of all three clusters. The z-standardization of Model 1 reveals that *logPopulation* and *GDPpC* β-weights are the most influential IVs, indicating that potential customer count and wealth substantially influence the number of available SDCs. Besides the socio-economic factors, the β-coefficients reveal that *non-fragile political contexts with fewer neighboring countries* also significantly promote the SDC diversity in a country-year. Model 2, the robust regression model of the same variables, reveals similar results, with no deviations in the mathematical signs and t-values roughly similar to the β-weights of Model 1.

5.2. Results for socio-economic factors

H1 hypothesized a positive correlation between socio-economic performance and the *DV*. The results of Model 2 confirm the positive correlation of *GDPpC* with the number of SDC planned and active accesses, implying that better socio-economic performance leads to more SDC construction projects and diverse availability of accesses. For the *DV*, the *GDPpC* has the highest explanatory value compared to other significant factors. This finding backs up H1 and is in line with previous, more general findings on the attractiveness of the telecommunications market in economically wealthy countries.

H2 theorized that a larger population and, thus, more potential customers would lead to more SDC access points and a higher probability of new SDC projects. For the *DV*, there is a positive correlation with *logPopulation* on the 0.001 level of significance. Moreover, in both models, population is the most influential factor. By this, we can confirm H2, indicating that a centralizing trend for SDC build-up is not only there for economic wealth but also for countries of large populations. Altogether, the economic markers for a country's wealth and population

Table 2
Multiple regression models for the number of active and planned SDC route accesses (DV) per country-year. Significance codes: '***': <0.001; '**': <0.01; '*': <0.05.

Independent variables	Hypotheses	Model 1 coefficients (*p*-value)	Model 1 β-coefficients (z-standardized)	Model 2 robust coefficients (t-value)
Intercept		−3.659e+02 (<2e-16 ***)		−271.592 (−38.774)
Time	*CV*	1.751e-01 (<2e−16 ***)	0.318	0.1314 (37.462)
GDPpC	*H1*	9.000e-05 (<2e-16 ***)	0.359	0.0001 (34.843)
logPopulation	*H2*	21737e+00 (<2e-16 ***)	0.622	1.560 (39.431)
State Fragility	*H3*	−1.928e-01 (2.33e-13 ***)	−0.098	−0.0959 (−6.778)
Conflict	*H4*	−9.151e-01 (9.96e-14 ***)	−0.063	−0.261 (−2.695)
Seismic Hazard	*H5*	1.331e-01 (4.70e-13 ***)	0.082	0.0757 (7.228)
Neighbors	*H6*	−2.132e-01 (<2e-16 ***)	−0.125	−0.096 (−6–797)
Multiple R^2		0.435	0.435	
Adjusted R^2		0.434	0.434	
p-Value		<2.2e-16 ***	<2.2e-16 ***	

appear to be essential factors in shaping the global SDC structure.

5.3. Results for political factors

H3 suspected a negative link of state fragility to the DV. *Fragility* represented by the FSI returned significant coefficients in the suspected direction. This shows the validity of our assumption; fragile countries are associated with a lower probability of attracting new SDC projects and an overall lower access diversity, which suggests that they seem to be uninviting contexts for SDC planners in general. Fragility moderately influences the general model, with β-coefficients of −0.098 in Model 1.

H4 suspected a negative link between violent conflict occurrence and the DV. Models 1 and 2 returned a negative estimate, the coefficient reached the 0.001 level of significance. This means that an occurrence of conflicts in a country-year reduces the expected number of SDC accesses by 0.9.

5.4. Results for geographic factors

H5 assumed *negative* correlations between the number of *neighboring countries* and a country's level of integration into the SDC network. The output for the *neighbors* coefficient was negative and significant – supporting the hypothesis that the number of neighboring countries is negatively correlated with the dependent variable. Countries with fewer neighbors – specifically island states that have zero neighbors – have fewer options for terrestrial cables and thus have a greater need for new SDC projects.

Lastly, H6 proposed a negative link between exposure to seismic hazards and the DV. As hypothesized, we found a significant ($p < 0.001$) positive correlation between *seismic hazard* and the *DV.* We interpreted this result as an indicator that, in the long run, operators opt for more redundancy in countries frequently struck by stronger seismic events, thereby displaying higher scores of active and planned accesses.

5.5. Post-tests

The model has been run through several post-tests. First, to test for excessive interaction between the IVs, we performed variance inflation factor (VIF) tests for. In neither model, the VIFs were above the threshold value of 5 (Menard, 1995). Thus, multicollinearity on a problematic level can be ruled out for our models. The VIF of Models 1 and 2 is shown in Table 3 below.

The histogram of residuals depicts a steep distribution with slightly unbalanced residuals for Model 1 (Fig. 2). Lacking normal distribution is confirmed through significant Shapiro-Wilk (Model 2: 0.1107 ***) statistics. Model 1, therefore, does not meet the requirement of normally distributed residuals. However, because of the central limit theorem, the larger the sample size, the looser this requirement becomes. Normal distribution for low-*n* samples is more important, as outliers may influence the results more strongly. With an *n* of 4916 complete observations (country-years without missing values in any of the variables) and <10 % of the statistical population of country-years (5261) missing, this requirement can be discarded for the models.

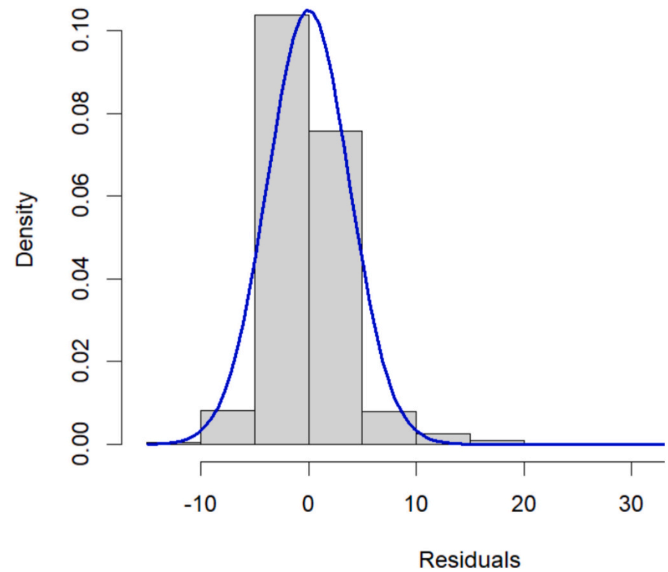

Fig. 2. Histogram of residuals for model 1.

6. Discussion

Confirming previous findings from technical SDC literature, we found that economic factors have primarily impacted the telecommunication companies in the backbone expansion. Regarding the *β*-weights, population and wealth were the factors with the greatest explanatory value in our models. However, we found indications for a broader set of additional factors that drove the decision-making of SDC construction. The DV shows a strong correlation to the political factor of state fragility and, to a lesser degree, with violent conflict occurrence. Fragile contexts seem to deter SDC planners from constructing broadly accessible internet infrastructures. Furthermore, geographic factors appear to influence the SDC accesses. The cumulated active and planned SDC count in country-years seems to be higher in countries that generally experience more seismic hazards. Finally, neighboring countries are a relevant marker for the DV. The number of neighboring countries seems to be negatively correlated with the DV, suggesting that countries with more neighbors have fewer SDC constructions.

In the following, the present study and its findings are contextualized in the current state of research (6.1), analytical and interpretative limitations are outlined (6.2), and an outlook on possible subsequent research projects is given (6.3).

6.1. Results in the light of current research

As presented in the related works, the quantitative analysis of a broader set of factors in SDC decision-making is in its early stages, while many hypotheses for influencing factors remain unchecked with regard to the global network. Most current analyses resort to network analysis tools that are advantageous in identifying the network's structure. Nevertheless, network analysis is limited in its capacity to include multiple factors unrelated to the network's own properties. Few works have so far combined network analysis results with inferential statistics, with Ross (2014) and Anonymized Authors (2022) as exceptions. Other works focus on singular influences for SDC planning, such as earthquakes (Wang et al., 2019b; Winseck, 2017; Yincan et al., 2018), ignoring the vast array of other potential factors. Moreover, others approach the topic with a regional focus (Bueger et al., 2022; Cariolle, 2019; Paximadis and Papapavlou, 2021; Saunavaara and Salminen, 2020), limiting the potential to make global statements based on their results.

With the presented study results, we identified influential factors in

Table 3
Variance inflation factor (VIF) results for Models 1 and 2.

	Time	GDPpC	LogPop	Fragility	Conflict	Seismic hazard	Neighbours
VIF	1.023	1.551	1.852	1.419	1.184	1.024	1.729

all clusters: socio-economic, political, and geographic. While the results support the dominance of economic motives of cable installers during SDC planning, the sole consideration of these factors seems inadequate regarding the significant estimates of *fragility*, *violent conflicts, neighbors*, and *seismic hazards*. Therefore, these results contrast previous explanations within the technical industry discourse on internet proliferation that mainly focused on the economic properties of countries. Such approaches to the construction, operation, and maintenance of public infrastructure may give a sufficient explanation of empirical economic data yet does not include factors beyond the economic regime of public telecommunication infrastructure and its local construction and global distribution. By including additional factors – theorized in social science literature but never tested quantitatively before – we widened the scope toward a more factor-inclusive analysis. This shows the value of theoretical and explorative works on the SDC network such as, inter alia, Starosielski (2015) and Gjesvik (2023). Consequently, the results show that future analysts of the worldwide build-up and expansion of the SDC backbone network should approach it through multifactorial methods. One-sided explanations may be helpful for further hypothesis generation, but their empirical testing should fundamentally include an appropriate selection of the covariates identified in this paper.

6.2. Limitations

The analysis is not without a few limitations. The first two concern the interpretation of the above results. Operationalizing country-years as research units leads to the countries' treatment as black boxes about their internal differences on different levels, e.g., regional and local variations in internet access, digital literacy, and investments. This restriction renders statements about the internal conditions of internet accessibility of states based on our data impossible. Nevertheless, we have accepted this constraint to provide a global analysis. At the same time, as posts test found unbalanced residuals and region- and time-specific subgroup follow-up analyses showed variance in the effects between countries, it is essential to interpret the factors presented here as global statements, which may well vary for individual country cases. Both limitations serve as a reminder to interpret the data on the global level. Future research may explore region- or country-specific factors in more depth – either through quantitative means like inferential statistics and network analyses, or by qualitative approaches that could explore the industry's perceived motivations (Gjesvik, 2023), media coverage of SDCs (Franken et al., 2023), and regulative aspects such as permitting, licensing and critical infrastructure regulations that are difficult to quantify.

Second, the data quality over time is quite good in the multiple datasets offered for the DV. The World Bank's DataBank served as the central resource for the IVs. It offers three measures for the statistical capacities of the countries, as government authorities provide many DataBank statistics (World Bank, 2021). While most reporting countries reach reasonably good values on the 0–100 scale, some are characterized by below-average scores, indicating potential issues with the quality of the methodology, periodicity, or data source. However, we still applied those values due to the lack of alternatives. Concerning the large-*n* sample, this limitation reiterates to interpret the values on the global scope. For case studies or small-*n* approaches, researchers should refrain from using the given data set but collect and verify their own, more granular data.

Third, Gunkel (2003) provides an excellent argumentative basis for criticisms of the general research landscape on technological proliferation, including techno-determinism. Recent developments indicate that the integrative and supportive perception of the internet during its development was incorrect. Although this appeared to be a general trend until the early 2000s, the purely optimistic attitude must be put aside at the latest since the negative consequences of internet use, such as authoritarian mass surveillance, disinformation, and growing dependency on CI began to emerge (Franken and Reuter, 2024). It should therefore be noted that all the statistics presented above are not imperative. Some coastal countries are statistically atypical but connected to the network early and still have diverse accesses. Therefore, the emphasis of the above regression analyses is on likelihoods, not inevitabilities. It is crucial not to perceive the internet as access to a determined utopian future but rather with *"space and place-based constraints"* (Haffner, 2017, p. 103) of the infrastructure and its use(*r*)s.

6.3. Further research

The theoretical foundations of factors of broadly accessible internet expansion are far more advanced than their empirical testing. This situation offers vast potential for future quantitative research as many factors still require verification through inductive approaches like inferential statistics. Future researchers may incorporate a broader set of variables to refine further the understanding of factors influencing SDC installation decisions. One promising area for exploration is the detailed characteristics of the cables, such as capacity, technological specifications, architecture, and expected lifespan. These attributes could provide valuable insights into how the technical evolution of SDCs impacts their deployment, especially as technology advances and the demands on global data infrastructure continue to grow. However, obtaining consistent and detailed data on these technical aspects across different cable systems may prove challenging, as such information is often proprietary or fragmented across different sources. Similarly, the properties of CLS could be a fruitful area of investigation. Factors such as the security and technological capabilities of CLS sites, along with their vulnerability to natural disasters, may significantly influence their selection as hubs for SDC networks. Researchers could explore how these factors interact with regional geopolitical stability and economic conditions. Nonetheless, comprehensive data on CLS properties might be difficult to acquire, particularly in regions where infrastructure details are closely guarded or not systematically reported.

Route properties, including the length and complexity of underwater cable paths, are another critical variable that could enhance the analysis of SDC projects. The challenges posed by topographical features, such as underwater mountains or seismic fault lines, could significantly affect the cost and feasibility of cable installations. However, the availability of precise and uniform data on these geographical factors may be limited, particularly for historical projects or in less-studied regions of the world. Researchers should also consider the impact of the digital economy as a pull factor for SDC installations. The proliferation of digital infrastructure, including secure internet servers, data centers, and Internet Exchange Points, has become increasingly important since the mid-2000s. This digital infrastructure is likely to attract more SDC projects as global data needs grow. However, consistent and longitudinal data on the growth and distribution of these digital assets are to be only available from certain periods or regions, potentially limiting the scope of analysis on the temporal axis. On a more granular level, the presence of large telecommunications companies and cable-laying facilities (production sites, capable vessels, personnel, and port facilities) could also be beneficial to a country's international connectivity.

Moreover, the influence of political factors, such as government funding for digital infrastructure and the governance of SDCs, warrants closer examination. These variables could reveal how national policies and international agreements shape the deployment of SDCs, particularly in developing or politically volatile regions. Yet, the challenge here lies in the variability and sometimes opacity of political data, which can make cross-country comparisons difficult. Furthermore, governments increasingly consider enhancing the protection of SDCs at the legal and governance level, often through maritime cable protection zones (Matley, 2019), or even sensor technology requirements, which both raise costs of installation. Few protection regimes are implemented at present, but marine zoning can also be considered a possible future pull factor – safeguarding SDCs from frequent outages and reducing maintenance costs. Lastly, political variables such as the dyadic relationship with neighboring states (economic sanctions, territorial disputes) or the geopolitical situation may shape the SDC expansion (Hamel, 2024).

Finally, researchers might explore additional socio-economic indicators, such as Gross National Product, national debt levels, or obligations to international financial institutions like the IMF. These factors could offer deeper insights into the economic motivations or constraints influencing SDC investments. Especially, if countries and markets transition from secondary to tertiary sector, the expansion of internet penetration into low-connected regions can trigger a race by state actors over economic control of such emerging markets. However, the availability and comparability of these economic indicators can vary, particularly in less economically developed countries, where data collection practices can be less rigorous. Moreover, in recent years, large cloud service and content providers (most importantly Meta, Microsoft, Amazon, and Google) have emerged as SDC installers or investors (Mauldin, 2021). By forming a subset of SDC projects with content provider participation, scholars could investigate whether these projects follow the traditional industries' patterns or choose an atypical SDC route planning, as Gjesvik (2023) suggests. Centralization of media is already a fact for large tech companies (Wu, 2010), yet studies on the influence of such private data hegemony for the overall structure of the internet connectivity and the spectrum of available services may be of special interest for future work.

A final phenomenon of little attention is SDC project cancelation during the various planning stages. At about two cancellations per annum, these events rarely occur but could provide interesting insights about the factors that are disadvantageous to internet infrastructure expansion.

6.4. Conclusion

This work aimed to answer the research question of what factors influenced the access of coastal and island countries to the SDC network between 1995 and 2025. We went beyond the technological and industry's focus on mainly economic motives and took a broader perspective on potential influence(d) the structure of the SDC infrastructure. Previous, mostly theoretical works of various disciplines suggested many additional factors. These led us to formulate six hypotheses on different factors grouped into socio-economic, political, and geographic clusters. We modeled the DV as the number of active and planned SDC connections. For the analysis, we created a country-year coded data set ($n = 4916$) for all coastal and island states and overseas territories and time-lagged the number of newly constructed cables five years later to model the decision context by the beginning of the SDC route planning process.

Indicators of better socio-economic performance proved to have a significant, positive impact on the DV. GDP per capita and population proved influential factors in all models we composed. The results on the political factors side were also conclusive: The conflict estimate led to significant estimates of the DV, and state fragility was negatively related to the cumulated SDC access count. Concerning geographic factors, seismic hazards were positively correlated, while the number of neighboring countries was negatively correlated to the cumulative count of active and planned SDC accesses (DV). While, as the weighted coefficients show, the political and geographic factors were less impactful than the economic factors, they nevertheless have a significant influence. Thus, these results revealed that the industry and technological discourse's narrative of mainly economic cost-benefit motives for cable planning is simplistic. Furthermore, the political fragility of states and violent conflicts pose risk factors that seem to be avoided by many cable-installing companies and conglomerates. Additionally, geographic factors determine the accessibility to alternative physical internet infrastructure. These findings emphasize future research's obligation to include the political context and geographic properties of coastal and island countries for future structural SDC analysis.

Given the internet's importance for society as a critical infrastructure, as well as for the economy and culture, public knowledge of its functioning and structure is essential. While the digitalization of society and businesses moves ahead, policymakers must understand the SDC network as a resource for human development and power and value projection sphere (Acheampong et al., 2022; Farrell and Newman, 2019). Recently, Bueger et al. coined the concept of *"cable diplomacy"* (2022, p. 46 f.), implying that internet infrastructures hold great potential for international development cooperation, which is mirrored in the EU Commission's recommendation to fund Cable Projects of European Interest (European Commission, 2024). Moreover, since the sabotages of the Nord Stream pipeline and multiple anchor drag incidents in the Baltic Sea, the security of maritime critical infrastructures, in general, has been called into question. Especially for countries lacking redundancies, sabotages and unintended damages pose a considerable threat to internet provision (Anonymized Authors, 2022). Therefore, overcoming the invisibility of the SDC network as the internet's central transmission infrastructure is a crucial challenge. Identifying the underlying, sedimented structures of the broad access expansion opens opportunities to address the inequitable distribution of digital access and resiliency through more accurately allocated telecommunication infrastructure development approaches. These findings could then inform the decision-making process for the foreseeable expansion of fixed maritime networks, such as intercontinental energy connectors and pipelines as well as international ports and energy terminals.

CRediT authorship contribution statement

Jonas Franken: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Thomas Reinhold:** Writing – original draft, Supervision, Conceptualization. **Timon Dörnfeld:** Writing – review & editing, Visualization. **Christian Reuter:** Supervision, Project administration, Funding acquisition.

Acknowledgments

This research work has been funded by the German Federal Ministry of Education and Research and the Hessian Ministry of Science and Research, Arts and Culture within their joint support of the National Research Center for Applied Cybersecurity ATHENE. The authors would like to thank Paula Meissner for general support of the paper.

Data availability

Data will be made available on request.

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