Online supplement to 'Methods for strategic liner shipping network design'

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Appendix A. Data

Ports

The ports considered in this study are obtained by merging all routes in the Asia-Europe trade lane of Maersk during spring 2010. Port Los Angeles is removed from the list, because it is not on the Asia-Europe trade lane. The 58 remaining ports, countries and regions can be found in natural order in Table A.1.

Distance

The distances between ports can be computed using distance calculators on the internet. The distances between the port combinations can be found in Table A.2.

Demand

In the cargo routing model it is important to know the demand between two ports. However, it is hard to achieve realistic data on the demand. The demand data is obtained from Lachner & Boskamp (2011). First, they determine total demand to be allocated on the Asia-Europe trade lane. This is done using annual reports of Maersk. Furthermore, a growth percentage is included in the calculation and corrections are made for joint services. Thereafter, the total demand is divided over port combinations using port throughput. The port throughput of both the origin and the destination port is used to determine the demand of a port combination. The demand that is generated in this way can be found in Table A.4.

Revenue

The revenue data is also obtained from Lachner & Boskamp (2011). It is assumed that the revenue per unit only depends on the distance between the origin and destination port of the demand and on the direction in which the demand has to be transported. Thereto,

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two revenue factors are introduced. The first factor gives the revenue of transporting one unit of cargo over one nautical mile in the westbound direction. The other revenue factor gives the revenue of transporting one unit of cargo over one nautical mile in the eastbound direction. Then, for each port combination, it is checked whether cargo has to be transported in westbound or eastbound direction. Finally, the corresponding revenue factor is multiplied with the direct distance between origin and destination port, which gives the revenue per unit of the considered port combination.

Lachner & Boskamp obtained the revenue by taking the 10-year average of historical data. This calculation gives the revenue in USD/TEU for both the eastbound and the westbound direction. Thereafter, they divided these revenues by the average distance between Asian and European ports. This results in the two revenue factors. The revenue factor is 0.0838 USD/nm in eastbound direction and 0.1677 USD/nm in westbound direction.

Available ships

In Francesetti & Foschi (2002) an overview of costs related to ships with different sizes is given. The ship sizes given in this article are also used in this study. Furthermore, some additional ship sizes are added in this study. The costs of these added ships are obtained by extrapolation on the costs given in Francesetti & Foschi (2002). The available ship sizes for both the main and feeder services can be found in Tables A.6 and A.7. In this study, it is assumed that an unlimited number of feeder ships is available.

Speed

From Notteboom (2006) it is learned that the speed of container vessels varies between 18 and 26 nautical miles per hour. Therefore, this range of speeds is also considered in this study. Furthermore, it is assumed that the speed can each time be increased by 0.5 nm per hour. Thus, seventeen different values for liner shipping vessels are considered in this study.

Further, it is assumed that feeder ships sail at a constant speed. This speed is assumed to be 22 nautical miles per hour.

Capital and operating cost

In Francesett & Foschi (2002), the yearly capital costs are given by 10% of the purchase price of the ship. The factor of 10% is the amortization factor. The purchase prices are given for ships with different ship sizes. The purchase price of the ships considered in this study, that are not given in Francesetti & Foschi (2002) are determined by extrapolation.

The operating costs are defined as 5% of the purchase price of the ship plus 1.5 times the number of crew members times the average yearly wage of the crew. The crew size is multiplied by 1.5 to take illness and holidays into account. The factor 5% of the purchase price of the ship is used to take cost of maintenance, repairs, etcetera into account. On average, 18 crew members with an average yearly wage of about $\$50,000$ are present on a ship. The average yearly wage is obtained by correcting the yearly wage of Fraccesetti & Foschi (2002) for inflation.

An overview on the yearly capital and operating costs per ship size can be found in Tables A.6 and A.7.

Fuel cost

The fuel consumption in ton per day is given for the different ship sizes in Francesetti & Foschi (2002) for a speed of 25 nm per hour. When this amount is divided by the distance travelled per day, the fuel consumption in ton per nautical mile is obtained. Thereafter, the fuel consumption is multiplied by the oil price in USD/ton to obtain the fuel cost in USD per nautical mile for the different ship sizes. In this study an oil price of 500 USD per ton is used in the calculations.

In Notteboom (2006) a figure is given that shows the fuel consumption in ton per day for different values of the sailing speed for a ship with capacity of almost 8500 TEU. The relation between fuel consumption and sailing speed will be about the same for different ship sizes. Therefore, this figure can be used to determine factors that indicate how much oil is consumed at different sailing speeds. Finally, these factors can be used to determine the fuel cost in USD per nautical mile for the other sailing speeds of the considered ships.

In Table A.8 an overview of the fuel cost for the different liner ship sizes and sailing speeds is given. The fuel costs for feeder ships are obtained in a similar way and are given in Table A.7.

Port, (un)loading and transhipment cost

The port, (un)loading and transhipment cost are obtained from Lachner & Boskamp (2011). Port costs are incurred per port visit and usually vary between ports. Furthermore, the port costs may depend on the ship size. However, the differences in port costs are relatively small, so they are assumed to be constant per route type. In this study, ships are charged 25,000 USD per port visit on a main route and 15,000 USD per port visit on a feeder route. Thus, when a port is visited on a main route $52 \cdot 25,000 = 1,300,000$ USD is charged, because each route is performed once a week. For feeder routes, the port cost per year equals $52 \cdot 15,000 = 780,000$ USD.

(Un)loading and transhipment costs are incurred per TEU (un)loaded or transhipped in a port. These costs can differ between ports and for different ship sizes. However, it is again assumed that these costs are constant per route type. The cost of (un)loading is 175 USD per TEU on main routes and 125 USD per TEU on feeder routes. A transhipment consist of a unloading and a loading movement, so the cost of a transhipment is $2 \cdot 175 =$

350 USD on main routes. Because each port (except the cluster centers) are only visited on one feeder route and no demand exists between ports in the same cluster, no transhipments will take place on feeder routes.

Port and buffer time

The time a ship spends in a port depends on many factors like the number of containers that have to be (un)loaded, the number of cranes available to (un)load, the arrival time, etcetera. However, these factors are uncertain, so it is difficult to determine these times. Therefore, port times are assumed to be constant. The data on these times are obtained from Lachner & Boskamp (2011). In this study, it is assumed that a ship spends 20 hour in a port on a main route and 15 hours in a port on a feeder route.

The buffer time is an additional time that is added to the route time to cover delays. The causes of delays can be divided in four groups: terminal operations, port access, maritime passages and chance (Notteboom (2006)). Chance includes weather conditions and mechanical problems. In this study, a buffer time of at least 2 days has to be allocated to each main route. The buffer time on feeder routes is assumed to be 1 day.

Port name	Country	Region	Port name	Country	Region
Yokohama	Japan	Asia	Port Said	Egypt	Middle East
Shimizu	Japan	Asia	Damietta	Egypt	Middle East
Nagoya	Japan	Asia	Izmit	Turkey	Europe
Kobe	Japan	Asia	Istanbul Ambarli	Turkey	Europe
Busan	South Korea	Asia	Odessa	Ukraine	Europe
Kwangyang	South Korea	Asia	Ilyichevsk	Ukraine	Europe
Dalian	China	Asia	Constantza	Romania	Europe
Xingang	China	Asia	Piraeus	Greece	Europe
Qingdao	China	Asia	Rijeka	Croatia	Europe
Liangyungang	China	Asia	Koper	Slovenia	Europe
Shanghai	China	Asia	Trieste	Italy	Europe
Ningbo	China	Asia	Gioia Tauro	Italy	Europe
Fuzhou	China	Asia	Genoa	Italy	Europe
Taipei	Taiwan	Asia	Fos	France	Europe
Xiamen	China	Asia	Barcelona	Spain	Europe
Kaohsiung	Taiwan	Asia	Valencia	Spain	Europe
Shenzhen Yantian	China	Asia	Malaga	Spain	Europe
Hong Kong	China	Asia	Algeciras	Spain	Europe
Shenzhen Chiwan	China	Asia	Tangiers	Marocco	Europe
Shenzhen Da Chan Bay	China	Asia	Le Havre	France	Europe
Vung Tau	Vietnam	Asia	Felixstowe	United Kingdom	Europe
Laem Chabang	Thailand	Asia	Zeebrugge	Belgium	Europe
Singapore	Singapore	Asia	Antwerp	Belgium	Europe
Tanjung Pelepas	Malaysia	Asia	Rotterdam	Netherlands	Europe
Port Klang	Malaysia	Asia	Bremerhaven	Germany	Europe
Colombo	Sri Lanka	Asia	Hamburg	Germany	Europe
Jebel Ali	Dubai	Middle East	Gothenburg	Sweden	Europe
Salalah	Oman	Middle East	Aarhus	Denmark	Europe
Jeddah	Saudi Arabia	Middle East	Gdansk	Poland	Europe

Table A.1: List of ports

Origin \ Destination	Yokohama	Shimizu	Nagoya	Kobe	Busan	Kwangyang	Dalian	Xingang	Qingdao	Liangyungang	Shanghai	Ningbo	Fuzhou	Taipei	Xiamen	Kaohsiung	Shenzhen Yantian	Hong Kong	Shenzhen Chiwan	Shenzhen Da Chan Bay	Vung Tau	Laem Chabang	Singapore	Tanjung Pelepas	Port Klang	Colombo	Jebel Ali	Salalah	Jeddah
Yokohama	0	96	188	333	626	679	1095	1246	1060	1086	1008	1020	1211	1134	1316	1319	1565	1582	1592	1597	2418	2972	2879	2899	3072	4431	6303	6045	7190
Shimizu	96	0	119	268	560	614	1030	1181	994	1020	942	954	1146	1064	1250	1254	1500	1516	1526	1531	2355	2907	2818	2838	3011	4370	6242	5984	7129
Nagoya	188	119	0	219	511	565	980	1132	945	971	893	905	1097	1028	1201	1205	1451	1467	1477	1482	2322	2858	2771	2791	2964	4323	6195	5937	7082
Kobe	333	268	219	0	341	394	810	961	775	801	729	761	999	917	1103	1107	1353	1369	1379	1384	2213	2760	2679	2699	2872	4231	6103	5845	6990
Busan	626	560	511	341	0	72	503	654	467	493	445	495	752	688	869	898	1120	1137	1147	1152	1977	2551	2483	2503	2676	4035	5907	5649	6794
Kwangyang	679	614	565	394	72	0	437	588	401	427	382	436	699	616	817	840	1062	1084	1094	1099	1905	2493	2428	2448	2621	3980	5852	5594	6739
Dalian	1095	1030	980	810	503	437	0	188	251	324	477	556	843	851	961	1006	1212	1229	1249	1244	2111	2659	2576	2596	2769	4128	6000	5742	6887
Xingang	1246	1181	1132	961	654	588	188	0	394	468	621	699	987	996	1105	1150	1356	1372	1382	1387	2242	2773	2720	2740	2913	4272	6144	5886	7031
Qingdao	1060	994	945	775	467	401	251	394	0	89	307	386	675	697	793	838	1044	1061	1071	1076	1959	2526	2408	2428	2601	3960	5832	5574	6719
Liangyungang	1086	1020	971	801	493	427	324	468	89	0	258	337	626	641	745	790	996	1012	1022	1027	1876	2407	2360	2380	2553	3912	5784	5526	6671
Shanghai	1008	942	893	729	445	382	477	621	307	258	0	101	390	421	509	554	760	776	786	791	1675	2242	2124	2144	2317	3676	5548	5290	6435
Ningbo	1020	954	905	761	495	436	556	699	386	337	101	0	318	355	436	481	687	704	714	719	1572	2103	2051	2071	2244	3603	5475	5217	6362
Fuzhou	1211	1146	1097	999	752	699	843	987	675	626	390	318	0	150	168	235	420	436	456	451	1318	1888	1784	1804	1977	3336	5208	4950	6095
Taipei	1134	1064	1028	917	688	616	851	996	697	641	421	355	150	0	222	224	446	471	481	486	1312	1877	1812	1832	2005	3364	5236	4970	6124
Xiamen	1316	1250	1201	1103	869	817	961	1105	793	745	509	436	168	222	0	166	270	287	297	302	1150	1714	1638	1658	1831	3190	5062	4804	5949
Kaohsiung	1319	1254	1205	1107	898	840	1006	1150	838	790	554	481	235	224	166	0	337	354	364	369	1121	1653	1611	1631	1804	3163	5035	4777	5922
Shenzhen Yantian	1565	1500	1451	1353	1120	1062	1212	1356	1044	996	760	687	420	446	270	337	0	46	56	61	947	1482	1436	1456	1629	2988	4860	4602	5747
Hong Kong	1582	1516	1467	1369	1137	1084	1229	1372	1061	1012	776	704	436	471	287	354	46	0	10	15	927	1489	1410	1430	1603	2962	4834	4576	5721
Shenzhen Chiwan	1592	1526	1477	1379	1147	1094	1249	1382	1071	1022	786	714	456	481	297	364	56	10	0	5	937	1499	1420	1440	1613	2983	4844	4586	5731
Shenzhen Da Chan Bay	1597	1531	1482	1384	1152	1099	1244	1387	1076	1027	791	719	451	486	302	369	61	15	5	0	942	1504	1425	1445	1618	2988	4849	4591	5736
Vung Tau	2418	2355	2322	2213	1977	1905	2111	2242	1959	1876	1675	1572	1318	1312	1150	1121	947	927	937	942	0	681	646	666	839	2198	4070	3796	4958
Laem Chabang	2972	2907	2858	2760	2551	2493	2659	2773	2526	2407	2242	2103	1888	1877	1714	1653	1482	1489	1499	1504	681	0	831	836	1009	2368	4240	3982	5127
Singapore	2879	2818	2771	2679	2483	2428	2576	2720	2408	2360	2124	2051	1784	1812	1638	1611	1436	1410	1420	1425	646	831	0	20	193	1552	3424	3166	4311
Tanjung Pelepas	2899	2838	2791	2699	2503	2448	2596	2740	2428	2380	2144	2071	1804	1832	1658	1631	1456	1430	1440	1445	666	836	20	0	173	1532	3404	3146	4291
Port Klang	3072	3011	2964	2872	2676	2621	2769	2913	2601	2553	2317	2244	1977	2005	1831	1804	1629	1603	1613	1618	839	1009	193	173	0	1370	3243	2985	4130
Colombo	4431	4370	4323	4231	4035	3980	4128	4272	3960	3912	3676	3603	3336	3364	3190	3163	2988	2962	2983	2988	2198	2368	1552	1532	1370	0	1887	1633	2788
Jebel Ali	6303	6242	6195	6103	5907	5852	6000	6144	5832	5784	5548	5475	5208	5236	5062	5035	4860	4834	4844	4849	4070	4240	3424	3404	3243	1887	0	894	2152
Salalah	6045	5984	5937	5845	5649	5594	5742	5886	5574	5526	5290	5217	4950	4970	4804	4777	4602	4576	4586	4591	3796	3982	3166	3146	2985	1633	894	0	1270
Jeddah	7190	7129	7082	6990	6794	6739	6887	7031	6719	6671	6435	6362	6095	6123	5949	5922	5747	5721	5731	5736	4957	5127	4311	4291	4130	2788	2152	1270	0
Port Said	7894	7833	7786	7694	7498	7443	7591	7735	7423	7375	7139	7066	6799	6822	6653	6626	6451	6425	6435	6440	5656	5837	5015	4995	4834	3492	2857	1975	715
Damietta	7925	7864	7817	7725	7519	7426	7622	7766	7454	7406	7170	7097	6830	6842	6674	6657	6482	6456	6466	6471	5668	5806	5036	5025	4854	3508	2888	2006	746
Izmit	8718	8650	8617	8518	8329	8278	8422	8566	8254	8206	7970	7898	7630	7644	7484	7450	7275	7256	7266	7271	6478	6654	5832	5825	5639	4303	3687	2805	1539
Istanbul Ambarli	8669	8608	8561	8469	8273	8219	8366	8510	8198	8150	7914	7841	7574	7591	7428	7401	7226	7200	7210	7215	6425	6599	5790	5770	5609	4267	3632	2750	1490
Odessa	9016	8955	8908	8816	8620	8539	8713	8857	8545	8497	8261	8188	7921	7938	7775	7748	7573	7547	7557	7562	6772	6956	6137	6117	5943	4607	3979	3097	1837
Ilyichevsk	9013	8941	8905	8809	8617	8526	8731	8870	8563	8494	8279	8185	7939	7935	7772	7741	7592	7565	7570	7575	6769	6943	6123	6114	5930	4594	3996	3094	1834
Constantza	8872	8811	8764	8672	8476	8422	8569	8713	8401	8353	8117	8044	7777	7794	7631	7604	7429	7403	7413	7418	6628	6802	5993	5973	5812	4470	3835	2953	1693
Piraeus	8481	8420	8373	8281	8085	8033	8178	8322	8010	7962	7726	7653	7386	7412	7240	7213	7038	7012	7022	7027	6246	6413	5602	5582	5421	4079	3444	2562	1302
Rijeka	9139	9078	9031	8939	8743	8691	8836	8980	8668	8620	8384	8311	8044	8070	7898	7871	7696	7670	7680	7685	6904	7071	6260	6240	6079	4737	4102	3220	1960
Koper	9178	9117	9070	8978	8782	8727	8875	9019	8707	8659	8423	8350	8083	8109	7937	7910	7735	7709	7719	7724	6943	7124	6299	6279	6117	4776	4141	3259	1999
Trieste	9186	9120	9078	8986	8790	8735	8883	9027	8715	8667	8431	8358	8091	8114	7945	7918	7738	7717	7727	7732	6948	7116	6302	6282	6109	4773	4149	3267	2007
Gioia Tauro	8822	8761	8714	8622	8426	8371	8519	8663	8351	8303	8067	7994	7727	7753	7581	7554	7379	7353	7363	7368	6587	6768	5943	5923	5762	4420	3785	2903	1643
Genoa	9305	9244	9197	9105	8909	8854	9002	9146	8834	8786	8550	8477	8210	8237	8064	8037	7862	7836	7847	7852	7071	7252	6426	6406	6245	4903	4268	3386	2126
Fos	9405	9344	9297	9205	9009	8954	9102	9246	8934	8886	8650	8577	8310	8332	8164	8137	7962	7936	7946	7951	7166	7340	6526	6506	6345	5003	4368	3486	2226
Barcelona	9476	9415	9368	9276	9080	9029	9173	9317	9005	8957	8721	8648	8381	8407	8235	8208	8033	8007	8034	8039	7241	7409	6597	6577	6416	5074	4439	3557	2297
Valencia	9556	9495	9448	9356	9160	9109	9253	9397	9085	9037	8801	8728	8461	8487	8315	8288	8113	8087	8097	8102	7321	7489	6677	6657	6496	5154	4519	3637	2377
Malaga	9758	9690	9650	9558	9362	9275	9455	9599	9324	9239	9040	8930	8663	8684	8517	8490	8315	8326	8336	8341	7518	7683	6872	6859	6679	5343	4758	3839	2579
Algeciras	9804	9743	9696	9604	9408	9340	9501	9645	9333	9285	9049	8976	8709	8735	8563	8536	8361	8335	8385	8390	7569	7736	6925	6905	6744	5402	4767	3885	2625
Tangiers	9835	9763	9728	9624	9440	9348	9533	9677	9365	9305	9081	9008	8741	8757	8595	8556	8393	8367	8410	8415	7591	7757	6945	6937	6752	5416	4799	3915	2657
Le Havre	10933	10872	10825	10736	10540	10485	10633	10774	10462	10414	10178	10105	9841	9864	9692	9668	9490	9467	9477	9482	8698	8879	8054	8034	7873	6534	5899	5014	3757
Felixstowe	11056	10995	10948	10856	10663	10605	10756	10897	10585	10537	10301	10228	9961	10013	9815	9788	9613	9587	9640	9645	8847	9014	8177	8157	7996	6657	6019	5137	3877
Zeebrugge	11083	11022	10975	10883	10687	10624	10780	10924	10612	10564	10328	10255	9988	10017	9842	9815	9640	9614	9624	9629	8851	9018	8204	8184	8023	6681	6046	5164	3904
Antwerp	11170	11109	11062	10970	10774	10711	10867	10986	10699	10626	10415	10317	10075	10078	9929	9902	9701	9701	9711	9716	8912	9077	8291	8246	8094	6758	6133	5234	3991
Rotterdam	11133	11072	11025	10933	10737	10688	10830	10974	10662	10614	10378	10305	10038	10081	9892	9865	9690	9664	9674	9679	8915	9082	8254	8234	8084	6742	6107	5214	3965
Bremerhaven	11328	11267	11220	11128	10932	10877	11025	11169	10857	10809	10573	10500	10233	10286	10087	10060	9885	9859	9889	9894	9120	9287	8449	8429	8268	6926	6291	5409	4149
Hamburg	11416	11355	11322	11216	11034	10971	11142	11242	10974	10882	10690	10573	10350	10334	10175	10148	9956	9976	9979	9984	9168	9332	8537	8502	8342	7006	6408	5490	4237
Gothenburg	11568	11507	11460	11368	11175	11117	11268	11409	11097	11049	10813	10740	10476	10524	10327	10300	10125	10099	10141	10146	9358	9525	8689	8669	8508	7169	6531	5649	4389
Aarhus	11662	11601	11554	11462	11269	11127	11419	11391	11248	11025	10964	10721	10615	10454	10421	10394	10276	10250	10258	10263	9453	9620	8783	8763	8602	7263	6682	5626	4483
Gdansk	11792	11731	11684	11592	11386	11293	11489	11633	11321	11273	11037	10964	10697	10833	10541	10524	10349	10323	10509	10514	9726	9893	8903	8892	8721	7375	6755	5873	4613

Table A.2: Distances between ports

Origin \ Destination	Port Said	Damietta	Izmit	Istanbul Ambarli	Odessa	Ilyichevsk	Constantza	Piraeus	Rijeka	Koper	Trieste	Gioia Tauro	Genoa	Fos	Barcelona	Valencia	Malaga	Algeciras	Tangiers	Le Havre	Felixstowe	Zeebrugge	Antwerp	Rotterdam	Bremerhaven	Hamburg	Gothenburg	Aarhus	Gdansk
Yokohama	7894	7925	8718	8669	9015	9013	8872	8481	9139	9178	9186	8822	9305	9405	9476	9556	9758	9804	9835	10933	11056	11083	11170	11133	11328	11416	11568	11662	11792
Shimizu	7833	7864	8650	8608	8954	8941	8811	8420	9078	9117	9120	8761	9244	9344	9415	9495	9690	9743	9763	10872	10995	11022	11109	11072	11267	11355	11507	11601	11731
Nagoya	7786	7817	8617	8561	8907	8905	8764	8373	9031	9070	9078	8714	9197	9297	9368	9448	9650	9696	9728	10825	10948	10975	11062	11025	11220	11322	11460	11554	11684
Kobe	7694	7725	8518	8469	8815	8809	8672	8281	8939	8978	8986	8622	9105	9205	9276	9356	9558	9604	9624	10736	10856	10883	10970	10933	11128	11216	11368	11462	11592
Busan	7498	7519	8329	8273	8619	8617	8476	8085	8743	8782	8790	8426	8909	9009	9080	9160	9362	9408	9440	10540	10663	10687	10774	10737	10932	11034	11175	11269	11386
Kwangyang	7443	7426	8278	8219	8539	8526	8422	8033	8691	8727	8735	8371	8854	8954	9029	9109	9275	9340	9348	10485	10605	10624	10711	10690	10877	10971	11117	11127	11293
Dalian	7591	7622	8422	8366	8712	8731	8569	8178	8836	8875	8883	8519	9002	9102	9173	9253	9455	9501	9533	10633	10756	10780	10867	10830	11025	11142	11268	11419	11489
Xingang	7735	7766	8566	8510	8856	8869	8713	8322	8980	9019	9027	8663	9146	9246	9317	9397	9599	9645	9677	10774	10897	10924	10986	10974	11169	11242	11409	11391	11633
Qingdao	7423	7454	8254	8198	8544	8563	8401	8010	8668	8707	8715	8351	8834	8934	9005	9085	9324	9333	9365	10462	10585	10612	10699	10662	10857	10974	11097	11248	11321
Liangyungang	7375	7406	8206	8150	8496	8494	8353	7962	8620	8659	8667	8303	8786	8886	8957	9037	9239	9285	9305	10414	10537	10564	10626	10614	10809	10882	11049	11025	11273
Shanghai	7139	7170	7970	7914	8260	8279	8117	7726	8384	8423	8431	8067	8550	8650	8721	8801	9040	9049	9081	10178	10301	10328	10415	10378	10573	10690	10813	10964	11037
Ningbo	7066	7097	7898	7841	8187	8185	8044	7653	8311	8350	8358	7994	8477	8577	8648	8728	8930	8976	9008	10105	10228	10255	10317	10305	10500	10573	10740	10721	10964
Fuzhou	6799	6830	7630	7574	7920	7939	7777	7386	8044	8083	8091	7727	8210	8310	8381	8461	8663	8709	8741	9841	9961	9988	10075	10038	10233	10350	10476	10615	10697
Taipei	6822	6842	7644	7591	7938	7935	7794	7412	8070	8109	8114	7753	8237	8332	8407	8487	8684	8735	8757	9864	10013	10017	10078	10081	10286	10334	10524	10454	10833
Xiamen	6653	6674	7484	7428	7774	7772	7631	7240	7898	7937	7945	7581	8064	8164	8235	8315	8517	8563	8595	9692	9815	9842	9929	9892	10087	10175	10327	10421	10541
Kaohsiung	6626	6657	7450	7401	7747	7741	7604	7213	7871	7910	7918	7554	8037	8137	8208	8288	8490	8536	8556	9668	9788	9815	9902	9865	10060	10148	10300	10394	10524
Shenzhen Yantian	6451	6482	7275	7226	7572	7592	7429	7038	7696	7735	7738	7379	7862	7962	8033	8113	8315	8361	8393	9490	9613	9640	9701	9690	9885	9956	10125	10276	10349
Hong Kong	6425	6456	7256	7200	7546	7565	7403	7012	7670	7709	7717	7353	7836	7936	8007	8087	8326	8335	8367	9467	9587	9614	9701	9664	9859	9976	10099	10250	10323
Shenzhen Chiwan	6435	6466	7266	7210	7556	7573	7413	7022	7680	7719	7727	7363	7847	7946	8034	8097	8336	8385	8410	9477	9640	9624	9711	9674	9889	9979	10141	10258	10509
Shenzhen Da Chan Bay	6440	6471	7271	7215	7561	7578	7418	7027	7685	7724	7732	7368	7852	7951	8039	8102	8341	8390	8415	9482	9645	9629	9716	9679	9894	9984	10146	10263	10514
Vung Tau	5656	5668	6478	6425	6772	6769	6628	6246	6904	6943	6948	6587	7071	7166	7241	7321	7518	7569	7591	8698	8847	8851	8912	8915	9120	9168	9358	9369	9726
Laem Chabang	5837	5806	6654	6599	6964	6951	6818	6413	7071	7124	7116	6759	7243	7340	7409	7489	7683	7736	7757	8882	9014	9018	9077	9082	9287	9332	9525	9507	9893
Singapore	5015	5036	5832	5790	6136	6123	5993	5602	6260	6299	6302	5943	6426	6526	6597	6677	6872	6925	6945	8054	8177	8204	8291	8254	8449	8537	8689	8783	8903
Tanjung Pelepas	4995	5025	5825	5770	6116	6114	5973	5582	6240	6279	6282	5923	6406	6506	6577	6657	6859	6905	6937	8034	8157	8184	8246	8234	8429	8502	8669	8763	8892
Port Klang	4834	4854	5639	5609	5943	5930	5812	5421	6079	6117	6109	5762	6245	6345	6416	6496	6679	6744	6752	7873	7996	8023	8094	8084	8268	8342	8508	8602	8721
Colombo	3492	3508	4303	4267	4607	4594	4470	4079	4737	4776	4773	4420	4903	5003	5074	5154	5343	5402	5416	6534	6657	6681	6758	6742	6926	7006	7169	7263	7375
Jebel Ali	2857	2888	3687	3632	3979	3996	3835	3444	4102	4141	4149	3785	4268	4368	4439	4519	4758	4767	4799	5899	6019	6046	6133	6107	6291	6408	6531	6682	6755
Salalah	1975	2006	2805	2750	3097	3094	2953	2562	3220	3259	3267	2903	3386	3486	3557	3637	3839	3885	3915	5014	5137	5164	5234	5214	5409	5490	5649	5626	5873
Jeddah	715	746	1539	1490	1837	1834	1693	1302	1960	1999	2007	1643	2126	2226	2297	2377	2579	2625	2657	3757	3877	3904	3991	3965	4149	4237	4389	4483	4613
Port Said	0	31	824	779	1126	1115	982	590	1248	1287	1294	931	1413	1513	1585	1665	1864	1913	1941	3042	3165	3195	3279	3256	3437	3525	3677	3771	3898
Damietta	31	0	848	793	1150	1137	996	607	1265	1307	1310	962	1434	1536	1603	1683	1877	1930	1951	3073	3196	3212	3271	3276	3468	3526	3707	3701	3867
Izmit	824	848	0	55	397	384	251	390	1150	1186	1190	837	1321	1420	1504	1588	1762	1643	1675	2798	3121	3062	3147	3126	3378	3261	3432	3535	3800
Istanbul Ambarli	779	793	55	0	347	344	203	349	1097	1137	1145	790	1273	1373	1460	1542	1731	1698	1730	2853	2976	2992	3079	3053	3248	3336	3487	3582	3829
Odessa	1126	1150	397	347	0	13	170	694	1444	1484	1492	1137	1620	1720	1807	1889	2078	2040	2156	3195	3391	3334	3421	3395	3663	3751	3903	3997	4244
Ilyichevsk	1115	1137	384	344	13	0	160	681	1441	1477	1481	1128	1612	1707	1798	1879	2075	2027	2059	3280	3305	3418	3397	3482	3687	3645	3816	3911	4184
Constantza	982	996	251	203	170	160	0	552	1300	1340	1348	993	1476	1576	1663	1745	1934	1894	2012	3049	3247	3188	3359	3249	3519	3607	3759	3853	4100
Piraeus	590	607	390	349	694	681	552	0	790	829	837	483	966	1066	1153	1235	1432	1484	1505	2614	2737	2773	2847	2834	3009	3095	3249	3343	3590
Rijeka	1248	1265	1150	1097	1444	1441	1300	790	0	103	110	581	1064	1164	1251	1338	1554	1603	1628	2732	2855	2892	2973	2953	3127	3215	3367	3461	3708
Koper	1287	1307	1186	1137	1484	1477	1340	829	103	0	8	620	1103	1202	1290	1377	1593	1642	1667	2772	2894	2931	3009	2992	3166	3254	3406	3500	3747
Trieste	1294	1310	1190	1145	1492	1481	1348	837	110	8	0	625	1109	1208	1296	1383	1598	1647	1672	2777	2925	2936	3014	3000	3205	3260	3436	3531	3804
Gioia Tauro	931	962	837	790	1137	1128	993	483	581	620	625	0	484	583	671	758	973	1022	1047	2152	2275	2311	2389	2372	2547	2635	2787	2881	3128
Genoa	1413	1434	1321	1273	1620	1612	1476	966	1064	1103	1109	484	0	208	350	508	798	847	871	1997	2100	2136	2213	2197	2372	2460	2630	2706	2953
Fos	1513	1536	1420	1373	1720	1707	1576	1066	1164	1202	1208	583	208	0	172	331	641	680	712	1830	1932	1969	2029	2030	2204	2285	2462	2538	2804
Barcelona	1585	1603	1504	1460	1807	1798	1663	1153	1251	1290	1296	671	350	172	0	161	499	513	545	1663	1786	1802	1881	1863	2058	2129	2297	2392	2639
Valencia	1665	1683	1588	1542	1889	1879	1745	1235	1338	1377	1383	758	508	331	161	0	338	382	411	1512	1635	1672	1752	1712	1907	1995	2147	2241	2488
Malaga	1864	1877	1762	1731	2078	2075	1934	1432	1554	1593	1598	973	798	641	499	338	0	65	87	1219	1343	1358	1429	1422	1627	1677	1854	1949	2222
Algeciras	1913	1930	1643	1698	2064	2054	1894	1484	1603	1642	1647	1022	847	680	513	382	65	0	32	1155	1278	1294	1370	1355	1550	1618	1789	1884	2131
Tangiers	1941	1951	1675	1730	2077	2059	1933	1505	1628	1667	1672	1047	871	712	545	411	87	32	0	1137	1273	1276	1347	1340	1545	1595	1786	1869	2154
Le Havre	3042	3073	2798	2853	3195	3280	3049	2614	2732	2772	2777	2152	1997	1830	1663	1512	1219	1155	1137	0	163	171	252	232	431	500	674	769	1015
Felixstowe	3165	3196	3121	2976	3323	3332	3179	2737	2855	2894	2925	2275	2100	1932	1786	1635	1343	1278	1273	163	0	83	141	123	303	360	530	606	872
Zeebrugge	3195	3212	3062	2992	3334	3336	3188	2773	2892	2931	2936	2311	2136	1969	1802	1672	1358	1294	1276	171	83	0	87	64	269	347	519	627	861
Antwerp	3279	3271	3147	3079	3421	3397	3280	2847	2973	3009	3014	2389	2213	2029	1881	1752	1429	1370	1347	252	141	87	0	149	356	405	597	680	965
Rotterdam	3256	3276	3126	3053	3395	3400	3249	2834	2953	2992	3000	2372	2197	2030	1863	1712	1422	1355	1340	232	123	64	149	0	215	305	467	584	809
Bremerhaven	3437	3468	3331	3248	3595	3605	3451	3009	3127	3166	3205	2547	2372	2204	2058	1907	1627	1550	1545	431	303	269	356	215	0	117	344	456	686
Hamburg	3525	3526	3261	3336	3683	3645	3539	3095	3215	3254	3260	2635	2460	2285	2129	1995	1677	1618	1595	500	360	347	405	305	117	0	402	485	770
Gothenburg	3677	3707	3432	3487	3834	3843	3690	3249	3367	3406	3436	2787	2630	2462	2297	2147	1854	1789	1786	674	530	519	597	467	344	402	0	151	368
Aarhus	3771	3701	3527	3582	3929	3938	3785	3343	3461	3500	3531	2881	2706	2538	2392	2241	1949	1884	1869	769	606	627	680	584	456	485	151	0	379
Gdansk	3898	3867	3800	3829	4176	4211	4032	3590	3708	3747	3804	3128	2953	2804	2639	2488	2222	2131	2154	1015	872	861	965	809	686	770	368	379	0

Table A.3: Distances between ports (2)

Origin \ Destination	Yokohama	Shimizu	Nagoya	Kobe	Busan	Kwangyang	Dalian	Xingang	Qingdao	Liangyungang	Shanghai	Ningbo	Fuzhou	Taipei	Xiamen	Kaohsiung	Shenzhen Yantian	Hong Kong	Shenzhen Chiwan	Shenzhen Da Chan Bay	Vung Tau	Laem Chabang	Singapore	Tanjung Pelepas	Port Klang	Colombo	Jebel Ali	Salalah	Jeddah
Yokohama	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9826	3083	2731
Shimizu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1756	551	488
Nagoya	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7419	2328	2062
Kobe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7891	2476	2193
Busan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41983	13171	11667
Kwangyang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6358	1995	1767
Dalian	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15986	5015	4442
Xingang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30552	9585	8490
Qingdao	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36031	11304	10013
Liangyungang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10608	3328	2948
Shanghai	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	87801	27546	24399
Ningbo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36884	11572	10250
Fuzhou	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4132	1296	1148
Taipei	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3512	1102	976
Xiamen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16436	5157	4568
Kaohsiung	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30136	9455	8374
Shenzhen Yantian	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42727	13405	11874
Hong Kong	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	73688	23118	20477
Shenzhen Chiwan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16023	5027	4453
Shenzhen Da Chan Bay	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5341	1676	1484
Vung Tau	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6496	2038	1805
Laem Chabang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16230	5092	4510
Singapore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	90837	28499	25243
Tanjung Pelepas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21071	6611	5855
Port Klang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25670	8054	7134
Colombo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12166	3817	3381
Jebel Ali	3215	575	2428	2582	13737	2080	5231	9997	11790	3471	28730	12069	1352	1149	5378	9861	13981	24112	5243	1748	2126	5311	29723	6895	8400	3981	0	0	0
Salalah	1009	180	762	810	4310	653	1641	3136	3699	1089	9014	3786	424	361	1687	3094	4386	7565	1645	548	667	1666	9325	2163	2635	1249	0	0	0
Jeddah	893	160	675	718	3818	578	1454	2778	3276	965	7984	3354	376	319	1495	2740	3885	6700	1457	486	591	1476	8260	1916	2334	1106	0	0	0
Port Said	1003	179	757	805	4285	649	1632	3118	3678	1083	8962	3765	422	358	1678	3076	4361	7521	1635	545	663	1657	9272	2151	2620	1242	0	0	0
Damietta	321	57	242	257	1370	207	522	997	1176	346	2865	1203	135	115	536	983	1394	2404	523	174	212	530	2964	687	838	397	0	0	0
Izmit	53	9	40	42	226	34	86	164	194	57	472	198	22	19	88	162	230	396	86	29	35	87	489	113	138	65	210	66	58
Istanbul Ambarli	621	111	469	499	2653	402	1010	1931	2277	670	5549	2331	261	222	1039	1904	2700	4657	1013	338	411	1026	5741	1332	1622	769	2469	775	686
Odessa	42	7	31	33	178	27	68	130	153	45	373	156	18	15	70	128	181	313	68	23	28	69	385	89	109	52	166	52	46
Ilyichevsk	32	6	24	26	137	21	52	100	118	35	287	121	14	11	54	99	140	241	52	17	21	53	297	69	84	40	128	40	36
Constantza	201	36	152	161	859	130	327	625	737	217	1796	754	85	72	336	616	874	1507	328	109	133	332	1858	431	525	249	799	251	222
Piraeus	475	85	358	381	2028	307	772	1476	1741	512	4241	1782	200	170	794	1456	2064	3560	774	258	314	784	4388	1018	1240	588	1887	592	524
Rijeka	49	9	37	39	210	32	80	153	180	53	438	184	21	18	82	150	213	368	80	27	32	81	453	105	128	61	195	61	54
Koper	116	21	88	93	496	75	189	361	426	125	1037	436	49	41	194	356	505	870	189	63	77	192	1073	249	303	144	461	145	128
Trieste	94	17	71	75	400	61	152	291	344	101	837	352	39	33	157	287	407	703	153	51	62	155	866	201	245	116	372	117	103
Gioia Tauro	947	169	715	761	4046	613	1541	2945	3473	1022	8462	3555	398	338	1584	2904	4118	7102	1544	515	626	1564	8755	2031	2474	1173	3765	1181	1046
Genoa	519	93	392	417	2216	336	844	1613	1902	560	4635	1947	218	185	868	1591	2256	3890	846	282	343	857	4795	1112	1355	642	2062	647	573
Fos	299	53	225	240	1275	193	486	928	1095	322	2667	1121	126	107	499	916	1298	2239	487	162	197	493	2760	640	780	370	1187	372	330
Barcelona	609	109	460	489	2601	394	991	1893	2233	657	5441	2285	256	218	1018	1867	2648	4566	993	331	403	1006	5629	1306	1591	754	2421	759	673
Valencia	1236	221	933	992	5280	800	2011	3843	4532	1334	11043	4639	520	442	2067	3790	5374	9268	2015	672	817	2041	11425	2650	3229	1530	4913	1541	1365
Malaga	98	18	74	79	419	63	160	305	360	106	876	368	41	35	164	301	426	735	160	53	65	162	906	210	256	121	390	122	108
Algeciras	1029	184	777	826	4397	666	1674	3200	3774	1111	9196	3863	433	368	1721	3156	4475	7718	1678	559	680	1700	9514	2207	2689	1274	4092	1284	1137
Tangiers	338	60	255	272	1445	219	550	1052	1240	365	3022	1270	142	121	566	1037	1471	2536	552	184	224	559	3127	725	884	419	1345	422	374
Le Havre	744	133	562	598	3179	481	1211	2314	2728	803	6649	2793	313	266	1245	2282	3236	5580	1213	404	492	1229	6879	1596	1944	921	2958	928	822
Felixstowe	1048	187	792	842	4480	678	1706	3260	3845	1132	9369	3936	441	375	1754	3216	4559	7863	1710	570	693	1732	9693	2248	2739	1298	4168	1308	1158
Zeebrugge	787	141	595	632	3364	510	1281	2448	2887	850	7036	2956	331	281	1317	2415	3424	5905	1284	428	521	1301	7280	1689	2057	975	3131	982	870
Antwerp	2472	442	1867	1985	10563	1600	4022	7687	9066	2669	22091	9280	1040	884	4135	7582	10750	18540	4031	1344	1634	4084	22855	5302	6459	3061	9829	3084	2731
Rotterdam	3295	589	2488	2646	14080	2132	5361	10247	12084	3558	29446	12370	1386	1178	5512	10107	14330	24713	5374	1791	2179	5443	30465	7067	8609	4080	13102	4110	3641
Bremerhaven	1534	274	1158	1232	6555	993	2496	4770	5625	1656	13708	5759	645	548	2566	4705	6671	11505	2502	834	1014	2534	14182	3290	4008	1899	6099	1914	1695
Hamburg	2371	424	1790	1904	10130	1534	3857	7372	8694	2560	21186	8900	997	847	3966	7271	10310	17780	3866	1289	1567	3916	21918	5084	6194	2936	9426	2957	2619
Gothenburg	277	49	209	222	1182	179	450	860	1014	299	2471	1038	116	99	463	848	1202	2074	451	150	183	457	2556	593	722	342	1099	345	306
Aarhus	231	41	174	186	987	149	376	718	847	249	2064	867	97	83	386	708	1005	1732	377	126	153	382	2136	495	604	286	918	288	255
Gdansk	81	15	61	65	348	53	132	253	298	88	727	305	34	29	136	250	354	610	133	44	54	134	752	175	213	101	324	102	90

Table A.4: Demand between ports

Origin \ Destination	Port Said	Damietta	Izmit	Istanbul Ambarli	Odessa	Ilyichevsk	Constantza	Piraeus	Rijeka	Koper	Trieste	Gioia Tauro	Genoa	Fos	Barcelona	Valencia	Malaga	Algeciras	Tangiers	Le Havre	Felixstowe	Zeebrugge	Antwerp	Rotterdam	Bremerhaven	Hamburg	Gothenburg	Aarhus	Gdansk
Yokohama	3065	980	138	1622	109	84	525	1240	128	303	245	2473	1355	780	1590	3228	256	2688	883	1943	2738	2057	6457	8606	4007	6192	722	603	213
Shimizu	548	175	25	290	19	15	94	222	23	54	44	442	242	139	284	577	46	480	158	347	489	368	1154	1538	716	1107	129	108	38
Nagoya	2314	740	104	1225	82	63	396	936	97	229	185	1868	1023	589	1201	2437	193	2029	667	1467	2068	1553	4875	6499	3025	4676	545	456	160
Kobe	2462	787	111	1302	87	67	422	996	103	243	196	1986	1088	626	1277	2592	206	2158	709	1561	2199	1652	5185	6912	3218	4973	580	484	171
Busan	13096	4186	590	6929	465	359	2243	5297	547	1295	1045	10567	5788	3331	6794	13790	1094	11484	3774	8303	11700	8787	27587	36772	17118	26456	3086	2578	908
Kwangyang	1983	634	89	1049	70	54	340	802	83	196	158	1600	877	504	1029	2088	166	1739	572	1257	1772	1331	4178	5569	2592	4006	467	390	138
Dalian	4986	1594	225	2638	177	137	854	2017	208	493	398	4024	2204	1268	2587	5251	417	4373	1437	3161	4455	3346	10504	14001	6518	10074	1175	981	346
Xingang	9530	3047	429	5043	339	261	1632	3854	398	943	761	7690	4212	2424	4944	10035	796	8357	2747	6042	8514	6394	20076	26760	12458	19253	2246	1876	661
Qingdao	11239	3593	506	5947	399	308	1925	4546	470	1112	897	9069	4967	2859	5831	11835	939	9855	3239	7126	10041	7541	23676	31558	14692	22705	2648	2212	779
Liangyungang	3309	1058	149	1751	118	91	567	1338	138	327	264	2670	1463	842	1717	3485	276	2902	954	2098	2956	2220	6971	9292	4326	6685	780	651	229
Shanghai	27388	8755	1234	14491	973	751	4691	11077	1144	2709	2186	22100	12105	6966	14209	28840	2288	24016	7893	17364	24468	18376	57694	76903	35801	55329	6453	5391	1899
Ningbo	11505	3678	518	6087	409	315	1970	4653	481	1138	918	9284	5085	2926	5969	12115	961	10089	3316	7294	10279	7719	24236	32305	15039	23243	2711	2265	798
Fuzhou	1289	412	58	682	46	35	221	521	54	127	103	1040	570	328	669	1357	108	1130	371	817	1151	865	2715	3619	1685	2604	304	254	89
Taipei	1095	350	49	580	39	30	188	443	46	108	87	884	484	279	568	1154	92	961	316	695	979	735	2308	3076	1432	2213	258	216	76
Xiamen	5127	1639	231	2713	182	141	878	2074	214	507	409	4137	2266	1304	2660	5399	428	4496	1478	3251	4580	3440	10800	14396	6702	10358	1208	1009	356
Kaohsiung	9400	3005	423	4974	334	258	1610	3802	393	930	750	7585	4155	2391	4877	9899	785	8243	2709	5960	8398	6307	19802	26395	12288	18990	2215	1850	652
Shenzhen Yantian	13328	4260	600	7052	473	365	2283	5390	557	1318	1064	10755	5891	3390	6914	14034	1113	11687	3841	8450	11907	8942	28076	37423	17422	26925	3140	2623	924
Hong Kong	22986	7348	1035	12162	816	630	3937	9296	961	2273	1835	18548	10159	5846	11925	24204	1920	20156	6624	14573	20535	15422	48420	64541	30046	46435	5416	4524	1594
Shenzhen Chiwan	4998	1598	225	2644	178	137	856	2021	209	494	399	4033	2209	1271	2593	5263	418	4383	1440	3169	4465	3353	10528	14034	6533	10097	1178	984	347
Shenzhen Da Chan Bay	1666	533	75	881	59	46	285	674	70	165	133	1344	736	424	864	1754	139	1461	480	1056	1488	1118	3509	4678	2178	3366	393	328	116
Vung Tau	2026	648	91	1072	72	56	347	820	85	200	162	1635	896	515	1051	2134	169	1777	584	1285	1810	1360	4268	5690	2649	4093	477	399	141
Laem Chabang	5063	1618	228	2679	180	139	867	2048	212	501	404	4085	2238	1288	2627	5331	423	4439	1459	3210	4523	3397	10665	14216	6618	10228	1193	997	351
Singapore	28335	9058	1276	14992	1007	777	4853	11460	1184	2802	2262	22864	12523	7207	14700	29837	2367	24847	8166	17965	25314	19012	59689	79562	37039	57242	6676	5577	1965
Tanjung Pelepas	6573	2101	296	3478	233	180	1126	2658	275	650	525	5304	2905	1672	3410	6921	549	5763	1894	4167	5872	4410	13846	18455	8592	13278	1549	1294	456
Port Klang	8007	2560	361	4237	284	220	1371	3239	335	792	639	6461	3539	2037	4154	8432	669	7022	2308	5077	7154	5373	16868	22484	10467	16177	1887	1576	555
Colombo	3795	1213	171	2008	135	104	650	1535	159	375	303	3062	1677	965	1969	3996	317	3328	1094	2406	3390	2546	7994	10656	4961	7667	894	747	263
Jebel Ali	0	0	180	2110	142	109	683	1613	167	394	318	3217	1762	1014	2069	4199	333	3496	1149	2528	3562	2675	8400	11196	5212	8055	940	785	277
Salalah	0	0	56	662	44	34	214	506	52	124	100	1009	553	318	649	1317	105	1097	361	793	1118	839	2635	3513	1635	2527	295	246	87
Jeddah	0	0	50	586	39	30	190	448	46	110	88	894	490	282	575	1167	93	972	319	703	990	743	2334	3111	1448	2239	261	218	77
Port Said	0	0	56	658	44	34	213	503	52	123	99	1004	550	316	645	1310	104	1091	358	789	1111	835	2620	3492	1626	2513	293	245	86
Damietta	0	0	18	210	14	11	68	161	17	39	32	321	176	101	206	419	33	349	115	252	355	267	838	1116	520	803	94	78	28
Izmit	66	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Istanbul Ambarli	770	246	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Odessa	52	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ilyichevsk	40	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Constantza	249	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Piraeus	589	188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rijeka	61	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Koper	144	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trieste	116	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gioia Tauro	1174	375	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Genoa	643	206	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fos	370	118	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Barcelona	755	241	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Valencia	1533	490	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Malaga	122	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Algeciras	1276	408	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tangiers	419	134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Le Havre	923	295	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Felixstowe	1300	416	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Zeebrugge	977	312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Antwerp	3066	980	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rotterdam	4087	1306	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bremerhaven	1903	608	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hamburg	2940	940	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gothenburg	343	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Aarhus	286	92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gdansk	101	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A.5: Demand between ports (2)

Ship Name	Ship Capacity (TEU)	Total Capacity (TEU/year)	Capital Cost ($/year)	Operating Cost ($/year)	Nr available
M1	4000	208000	4500000	3600000	5
M2	5000	260000	5400000	4050000	5
M3	6000	312000	6000000	4350000	5
M4	7000	364000	6500000	4600000	5
M5	8000	416000	7000000	4850000	5
M6	9000	468000	7500000	5100000	5
M7	10000	520000	8000000	5350000	2
M8	14000	728000	10000000	7850000	1

Table A.6: Liner ship characteristics

Ship Name	Ship Capacity (TEU)	Total Capacity (TEU/year)	Capital Cost ($/year)	Operating Cost ($/year)	Fuel cost ($/nm)
F1	200	10400	800000	1450000	16.667
F2	350	18200	950000	1525000	20.833
F3	500	26000	1100000	1600000	25.000
F4	700	36400	1400000	1750000	26.667
F5	800	41600	1500000	1800000	29.167
F6	900	46800	1600000	1850000	31.667
F7	1000	52000	1750000	1925000	33.333
F8	1250	65000	2100000	2100000	41.667
F9	1500	78000	2300000	2200000	50.000
F10	1750	91000	2500000	2300000	58.333
F11	2000	104000	2700000	2400000	66.667
F12	2250	117000	2950000	2525000	75.000
F13	2500	130000	3200000	2650000	83.333
F14	4000	208000	4500000	3600000	91.626
F15	5000	260000	5400000	4050000	104.264

Table A.7: Feeder ship characteristics

Ship	Speed																
Name	18	18.5	19	19.5	20	20.5	21	21.5	22	22.5	23	23.5	24	24.5	25	25.5	26
M1	85.637	84.925	84.250	83.610	83.002	83.870	84.696	88.242	91.626	94.860	101.820	108.483	114.869	120.995	126.875	132.525	137.957
M2	97.449	96.639	95.871	95.143	94.451	95.438	96.379	100.413	104.264	107.944	115.864	123.447	130.713	137.684	144.375	150.804	156.986
M3	109.261	108.353	107.492	106.675	105.900	107.006	108.061	112.584	116.902	121.028	129.908	138.410	146.557	154.372	161.875	169.083	176.014
M4	121.073	120.067	119.113	118.208	117.348	118.575	119.743	124.755	129.540	134.112	143.952	153.373	162.401	171.061	179.375	187.363	195.043
M5	132.886	131.780	130.734	129.740	128.797	130.143	131.425	136.927	142.178	147.196	157.996	168.336	178.245	187.750	196.875	205.642	214.071
M6	144.698	143.494	142.354	141.273	140.245	141.711	143.107	149.098	154.816	160.280	172.040	183.299	194.090	204.439	214.375	223.921	233.100
M7	156.510	155.208	153.975	152.805	151.694	153.280	154.790	161.269	167.454	173.364	186.084	198.263	209.934	221.128	231.875	242.200	252.129
M8	203.758	202.063	200.458	198.935	197.488	199.553	201.519	209.954	218.007	225.701	242.261	258.115	273.310	287.884	301.875	315.317	328.243

Table A.8: Fuel cost for different speeds and ship sizes

Appendix B. Reference network

Table B.9 shows the routes in the reference network during spring 2010. Next, Table B.10 shows the different types of ships used on each of the routes.

AE1/AE10	AE10/AE1	AE2	AE3	AE6
Yokohama	Shenzhen Yantian	Busan	Dalian	Yokohama
Hong Kong	Hong Kong	Xingang	Xingang	Nagoya
Shenzhen Yantian	Tanjung Pelepas	Dalian	Busan	Shanghai
Tanjung Pelepas	Le Havre	Qingdao	Shanghai	Ningbo
Felixstowe	Zeebrugge	Kwangyang	Ningbo	Xiamen
Rotterdam	Hamburg	Shanghai	Taipei	Hong Kong
Hamburg	Gdansk	Bremerhaven	Shenzhen Chiwan	Shenzhen Yantian
Bremerhaven	Gothenburg	Hamburg	Shenzhen Yantian	Tanjung Pelepas
Tangiers	Aarhus	Rotterdam	Tanjung Pelepas	Jeddah
Jeddah	Bremerhaven	Felixstowe	Port Klang	Barcelona
Jebel Ali	Rotterdam	Antwerp	Port Said	Valencia
Shenzhen Da Chan Bay	Singapore	Tanjung Pelepas	Damietta	Algeciras
Ningbo	Hong Kong	Busan	Izmit	Tangiers
Shanghai	Kobe		Istanbul Ambarli	Tanjung Pelepas
Kaohsiung	Nagoya		Constantza	Vung Tau
Yokohama	Shimizu		Ilyichevsk	Shenzhen Yantian
	Yokohama		Odessa	Hong Kong
	Shenzhen Yantian		Damietta	Yokohama
			Port Said	
			Port Klang	
			Tanjung Pelepas	
			Dalian	

AE7	AE9	AE11	AE12
Shanghai	Laem Chabang	Qingdao	Shanghai
Ningbo	Tanjung Pelepas	Shanghai	Busan
Xiamen	Port Klang	Fuzhou	Hong Kong
Hong Kong	Colombo	Hong Kong	Shenzhen Chiwan
Shenzhen Yantian	Zeebrugge	Shenzhen Chiwan	Tanjung Pelepas
Algeciras	Felixstowe	Shenzhen Yantian	Port Klang
Tangiers	Bremerhaven	Tanjung Pelepas	Port Said
Rotterdam	Rotterdam	Port Klang	Piraeus
Felixstowe	Le Havre	Salalah	Koper
Bremerhaven	Tangiers	Port Said	Rijeka
Malaga	Salalah	Gioia Tauro	Trieste
Shenzhen Yantian	Colombo	Genoa	Damietta
Hong Kong	Port Klang	Fos	Port Said
Shanghai	Singapore	Genoa	Jeddah
	Laem Chabang	Damietta	Port Klang
		Port Said	Singapore
		Salalah	Shanghai
		Port Klang	
		Singapore	
		Liangyungang	
		Qingdao	

Table B.9: Routes in the Maersk network

AE1/AE10	Capacity	AE10/AE1	Capacity	AE2	Capacity
Sofie Maersk	8160	A.P. Moller	8160	Maersk Seville	8478
Albert Maersk	8272	Skagen Maersk	8160	Maersk Saigon	8450
Carsten Maersk	8160	Sally Maersk	8160	Adrian Maersk	8272
Maersk Singapore	8478	Arnold Maersk	8272	Maersk Salina	8600
Clementine Maersk	8648	Svendborg Maersk	8160	Maersk Savannah	8600
Maersk Seoul	8450	Svend Maersk	8160	Anna Maersk	8272
Maersk Taurus	8400	Columbine Maersk	8648	Arthur Maersk	8272
Sine Maersk	8160	Maersk Tukang	8400	Maersk Stepnica	8600
Axel Maersk	8272	Clifford Maersk	8160	Maersk Semarang	8400
Cornelia Maersk	8650	Maersk Salalah	8600	Maersk Stralsund	8450
		Maersk Stockholm	8600		
Average	8365		8316		8439

AE3		AE6		AE7	
Maersk Kinloss	6500	Mathilde Maersk	9038	Eugen Maersk	14770
CMA CGM Debussy	6627	Maersk Antares	9200	Elly Maersk	14770
Maersk Kuantan	6500	Gunvor Maersk	9074	Evelyn Maersk	14770
Maersk Kowloon	6500	Mette Maersk	9038	Edith Maersk	14770
CMA CGM Corneille	6500	Marit Maersk	9038	Estelle Maersk	14770
Maersk Kelso	6500	Gerd Maersk	9074	Maersk Algol	9200
CMA CGM Musset	6540	Maersk Altair	9200	Ebba Maersk	14770
Maersk Kwangyang	6500	Gudrun Maersk	9074	Eleonora Maersk	14770
CMA CGM Bizet	6627	Marchen Maersk	9038	Emma Maersk	14770
Maersk Kensington	6500	Maren Maersk	9038	Gjertrud Maersk	9074
CMA CGM Baudelaire	6251	Georg Maersk	9074		
		Grete Maersk	9074		
		Maersk Alfirk	9200		
		Margrethe Maersk	9038		
Average	6504		9086		13643

AE9		AE11		AE12	
Maersk Sembawang	6478	Charlotte Maersk	8194	Maersk Kyrenia	6978
Maersk Sebarok	6478	Maersk Surabaya	8400	Safmarine Komati	6500
Maersk Serangoon	6478	Maersk Santana	8478	CMA CGM Belioz	6627
SL New York	6420	CMA CGM Faust	8204	Safmarine Kariba	6500
Maersk Seletar	6478	Soroe Maersk	8160	CMA CGM Balzac	6251
Maersk Kendal	6500	Susan Maersk	8160	Maersk Karachi	6930
Maersk Sentosa	6478	Caroline Maersk	8160	CMA CGM Ravel	6712
Maers Semakau	6478	Cornelius Maersk	8160	CMA CGM Flaubert	6638
Maersk Senang	6478	Chastine Maersk	8160	CMA CGM Voltaire	6456
Average	6474		8230		6621

Table B.10: Ships and capacities on the Maersk network

Appendix C. Cluster design

Table C.11 shows the composition of the ten clusters obtained after aggregation in this study.

Shanghai	Hong Kong	Singapore	Colombo	Jebel Ali
Yokohama	Xiamen	Vung Tau	Colombo	Jebel Ali
Shimizu	Kaohsiung	Laem Chabang		Salalah
Nagoya	Shenzhen Yantian	Singapore		
Kobe	Hong Kong	Tanjung Pelepas		
Busan	Shenzhen Chiwan	Port Klang		
Kwangyang	Shenzhen Da Chan Bay			
Dalian				
Xingang				
Qingdao				
Liangyungang				
Shanghai				
Ningbo				
Fuzhou				
Taipei				

Port Said	Valencia	Rotterdam	Antwerp	Hamburg
Izmit	Gioia Tauro	Zeebrugge	Antwerp	Bremerhaven
Odessa	Genoa	Le Havre		Hamburg
Jeddah	Fos	Felixstowe		Gothenburg
Port Said	Barcelona	Rotterdam		Aarhus
Damietta	Valencia			Gdansk
Istanbul Ambarli	Malaga			
Ilyichevsk	Algeciras			
Constantza	Tangiers			
Piraeus				
Rijeka				
Koper				
Trieste				

Table C.11: Design of the ten clusters

Appendix D. Best Network

M1	M2	M3	M4
Tanjung Pelepas	Shenzhen Yantian	Busan	Ningbo
Singapore	Shenzhen Chiwan	Qingdao	Busan
Port Klang	Shenzhen Da Chan Bay	Xingang	Qingdao
Colombo	Hong Kong	Dalian	Xingang
Gioia Tauro	Xiamen	Shanghai	Dalian
Valencia	Kaohsiung	Ningbo	Liangyungang
Algeciras	Singapore	Hong Kong	Shanghai
Felixstowe	Tanjung Pelepas	Shenzhen Chiwan	Fuzhou
Zeebrugge	Port Klang	Shenzhen Yantian	Hong Kong
Rotterdam	Port Said	Jeddah	Shenzhen Yantian
Bremerhaven	Felixstowe	Port Said	Xiamen
Hamburg	Le Havre	Bremerhaven	Kaohsiung
Rotterdam	Rotterdam	Hamburg	Algeciras
Damietta	Zeebrugge	Aarhus	Tangiers
Port Said	Port Klang	Gothenburg	Malaga
Jeddah	Tanjung Pelepas	Antwerp	Valencia
Tanjung Pelepas	Singapore	Algeciras	Fos
	Shenzhen Yantian	Valencia	Genoa
		Gioia Tauro	Barcelona
		Port Said	Gioia Tauro
		Jeddah	Ningbo
		Colombo	
		Shenzhen Chiwan	
		Hong Kong	
		Shenzhen Yantian	
		Busan	
9000	10000	14000	9000
M5	M6	M7	
Shenzhen Yantian	Ningbo	Shenzhen Yantian	
Shenzhen Chiwan	Qingdao	Shenzhen Chiwan	
Hong Kong	Busan	Shenzhen Da Chan Bay	
Xiamen	Xingang	Hong Kong	
Kaohsiung	Dalian	Xiamen	
Jebel Ali	Shanghai	Kaohsiung	
Salalah	Jebel Ali	Jeddah	
Antwerp	Valencia	Port Said	
Hamburg	Felixstowe	Damietta	
Bremerhaven	Le Havre	Shenzhen Yantian	
Rotterdam	Rotterdam		
Zeebrugge	Zeebrugge		
Algeciras	Antwerp		
Valencia	Port Said		
Barcelona	Singapore		
Gioia Tauro	Hong Kong		
Port Said	Ningbo		
Port Klang			
Tanjung Pelepas			
Singapore			
Vung Tau			
Shenzhen Yantian			
14000 TEU	9000 TEU	9000 TEU	8000 TEU

Table D.12: Main routes of the best network

Route	Capacity	Ports visited					
F01	350	Rotterdam	Le Havre	Felixstowe	Rotterdam		
F02	900	Shanghai	Liangyungang	Shanghai			
F03	2000	Shanghai	Ningbo	Nagoya	Yokohama	Shanghai	
F04	500	Shanghai	Fuzhou	Shimizu	Shanghai		
F05	2000	Shanghai	Taipei	Kobe	Kwangyang	Shanghai	
F06	1250	Hong Kong	Xiamen	Kaohsiung	Shenzhen Da Chan Bay	Hong Kong	
F07	2250	Singapore	Vung Tau	Laem Chabang	Singapore		
F08	1250	Hamburg	Aarhus	Gdansk	Gothenburg	Hamburg	
F09	200	Port Said	Jeddah	Port Said			
F10	1750	Port Said	Istanbul Ambarli	Izmit	Port Said		
F11	200	Port Said	Ilyichevsk	Odessa	Port Said		
F12	1750	Port Said	Piraeus	Constantza	Port Said		
F13	200	Port Said	Rijeka	Damietta	Port Said		
F14	700	Port Said	Trieste	Koper	Port Said		
F15	2250	Valencia	Tangiers	Genoa	Fos	Barcelona	Valencia
F16	200	Valencia	Malaga	Valencia			

Table D.13: Feeder routes of the best network

Appendix E. Solution approach

In this section, some solution methods are discussed in more detail.

Appendix E.1. Aggregation

First, we will describe the methods used to aggregate ports into port clusters. Thereto, we will first create lists of central, noncentral and intermediary ports. Thereafter, initial clusters will be designed, which are updated in the next step. After this step, the final clusters are known and the cluster data have to be constructed.

Appendix E.1.1. Lists of central, noncentral and intermediary ports

First, construct the lists of central, noncentral and intermediary ports:

$$\begin{aligned} \mathcal{H}^c &:= \{h \in \mathcal{H} : x_h \geq M\bar{x}\} && \text{central ports.} \\ \mathcal{H}^{nc} &:= \{h \in \mathcal{H} : x_h \leq m\bar{x}\} && \text{noncentral ports.} \\ \mathcal{H}^m &:= \{h \in \mathcal{H} : h \notin \mathcal{H}^c \cup \mathcal{H}^{nc}\} && \text{intermediary ports.} \end{aligned}$$

In this definitions, $\mathcal{H}$ is the set containing all ports, m and M are the minimum and maximum factor respectively. In our case study, we used $m = 0.2$ and $M = 2$. Further, when $d_{a,b}$ is the demand from port a to port b, we have:

$$\begin{aligned} x_h &= \sum_{h' \in \mathcal{H}} d_{h,h'} + \sum_{h' \in \mathcal{H}} d_{h',h} && \text{throughput of port } h; \\ \bar{x} &= \frac{1}{|\mathcal{H}|} \sum_{h \in \mathcal{H}} x_h && \text{average throughput per port.} \end{aligned}$$

Appendix E.1.2. Initial clusters

Next, we create initial clusters. For each $h_i \in \mathcal{H}^c$, create a new cluster $C_i := \{h_i\}$ (with $i = 1, \ldots, |\mathcal{H}^c|$) only containing port h_i and the central port of the cluster is $c_i = h_i$. Let I denote the number of clusters. Then, we have $I = |\mathcal{H}^c|$ initial clusters all containing exactly one port. Next, we will add intermediary and noncentral ports to the nearest existing cluster if they are within the maximum cluster distance. We will only compare the distance between the considered port and the central port of the cluster with the maximum cluster distance, because this distance has to be covered on the feeder lines. Thus, it is possible that the distance between two ports in the same cluster exceeds the maximum cluster distance, but these ports will then not be visited on the same feeder service. Thus, for each $h \in \mathcal{H}^{nc} \cup \mathcal{H}^m$, we will have

$$\begin{aligned} C_i &= C_i \cup \{h\} && \text{if} \quad D_{h,c_i} = \min_{1 \leq j \leq I} D_{h,c_j} \leq D^{max} \\ C_i &= C_i && \text{else,} \end{aligned}$$

where $D_{a,b}$ is the distance between port a and b and D^{max} the maximum distance allowed between ports in a cluster. In our case study we used $D^{max} = 1250$ nm, such that direct feeder lines between a port in the cluster and the central port of the cluster can always be served within one week.

Appendix E.1.3. Update clusters

Let

$$\begin{aligned} \mathcal{H}_a &:= \{h \in \mathcal{H}^{nc} \cup \mathcal{H}^m : h \in \cup_i C_i\} && \text{allocated ports.} \\ \mathcal{H}_{na}^m &:= \{h \in \mathcal{H}^m : h \notin \cup_i C_i\} && \text{nonallocated intermediary ports.} \\ \mathcal{H}_{na}^{nc} &:= \{h \in \mathcal{H}^{nc} : h \notin \cup_i C_i\} && \text{nonallocated noncentral ports.} \end{aligned}$$

As long as $\mathcal{H}_{na}^m \neq \emptyset$, take port $h \in \mathcal{H}_{na}^m$ with the largest throughput ($x_h = \max_{h' \in \mathcal{H}_{na}^m} x_{h'}$). Create a new cluster, $I = I + 1$ and $C_I = \{h\}$, $c_I = h$. Add intermediary and noncentral ports to the new cluster if they are nearest to this cluster and their distance is within the maximum distance allowed. That is, for each $h \in \mathcal{H}^{nc} \cup \mathcal{H}^m$, we will have

$$\begin{aligned} C_I &= C_I \cup \{h\} && \text{if} \quad D_{h,c_I} = \min_{j \leq I} D_{h,c_j} \leq M \\ C_I &= C_I && \text{else,} \end{aligned}$$

where $D_{a,b}$ is again the distance between port a and b and M the maximum distance allowed between ports in a cluster. For all port $h \in C_I$ check whether they were already allocated to a cluster, that is check whether

$$h \in \cup_{1 \leq i \leq I-1} C_i.$$

If the port was already allocated to a cluster, remove it from the cluster, so if $h \in C_j$ with $1 \leq j \leq I - 1$, then let $C_j = C_j \setminus \{h\}$. Update the sets with allocated and nonallocated ports and repeat this procedure until $\mathcal{H}_{na}^m = \emptyset$.

If $\mathcal{H}_{na}^{nc} \neq \emptyset$, then determine for each $h \in \mathcal{H}_{na}^{nc}$ to which cluster it is closest and add it to this cluster:

$$\begin{aligned} C_i &= C_i \cup \{h\} && \text{if} \quad D_{h,c_i} = \min_{1 \leq j \leq I} D_{h,c_j} \leq M \\ C_i &= C_i && \text{else.} \end{aligned}$$

The clusters C_i for $1 \leq i \leq I$ are the final clusters that will be used as input for the cargo routing model. It only remains to determine the relevant port cluster data, which will be explained in the next section.

Appendix E.1.4. Determine cluster data

To determine the profitability of a given network, the demand, distance and revenue between port pairs are needed. Furthermore, the (un)loading, transhipment and visit costs are needed for each port, as is the time of a port visit. The distance, costs and port time of a cluster are all incurred in the central port of the cluster, so we set:

$$\begin{aligned} D_{C_i,C_j} &= D_{c_i,c_j} \qquad 1 \le i,j \le I; \\ c_{C_i} &= c_{c_i} \qquad 1 \le i \le I; \\ t_{C_i} &= t_{c_i} \qquad 1 \le i \le I, \end{aligned}$$

where $D_{a,b}$ is the distance between port/cluster a and b, c_a denote the relevant costs of port/cluster a and t_a is the port time of port/cluster a. Furthermore, C_i denotes cluster i, while c_i is the central port of cluster i. Since it is not possible to determine the origin and destination port of a cargo flow between clusters when solving the cargo routing model, we let the revenue between port pairs be equal to the revenue between the central ports of the relevant clusters. That is, we let:

$$r_{C_i,C_j} = r_{c_i,c_j} \qquad 1 \le i,j \le I.$$

The demand between clusters depend on the demand between the ports in the clusters. Cluster demand equals the sum of all individual port demands in the cluster:

$$d_{C_i,C_j} = \sum_{h \in C_i} \sum_{h' \in C_j} d_{h,h'} \qquad 1 \le i,j \le I,$$

with $d_{a,b}$ the demand between ports/clusters a and b.

Appendix E.2. Disaggregation

In practice, it is necessary to know the exact origin and destination port of each cargo flow. Therefore, the cargo flows between port clusters have to be disaggregated into cargo flows between ports. This section will describe the method to obtain these disaggregated flows.

The disaggregation process can be performed for each combination of port clusters separately. Thus, select two port clusters C_i and C_j and the corresponding total flow over the network

$$f = \sum_{s \in \mathcal{S}} x^{tot}_{C_i,C_j,s}.$$

So, the total cargo flow from cluster C_i to cluster C_j over the network is equal to f. Now, we want to determine the origin and destination ports of the flow. Repeat the following until $f = 0$. Select the combination (h, h') with $h \in C_i$ and $h' \in C_j$ with the largest expected revenue. Now, allocate as much flow as possible to the combination (h, h'), so

$$f_{h,h'} = \min(d_{h,h'}, f),$$

where $d_{h,h'}$ is the demand between port h and h' and $f_{h,h'}$ is the allocated flow from port h to port h'. Update the flow to be allocated:

$$f = f - f_{h,h'}.$$

Appendix E.3. Feeder network

In the disaggregation phase, cargo flows between ports are determined. We will use feeder services to ship the cargo from and to ports in the cluster. After an initial feeder network is constructed, some methods are described to improve the network. These methods include reallocating demand in order to reduce the capacity on the feeder lines, exchanging ports between feeder lines and adding ports to the main route network. In this section, a description of these methods will be given.

Appendix E.3.1. Initial feeder network

In first instance, for each port in the cluster (except the central port) a direct feeder service is constructed between this port and the central port of the cluster. Let $\mathcal{F}^C$ be set of feeder services in cluster C, then

$$\mathcal{F}^C := \{(c, h, c) : h \in C \setminus \{c\}\} \qquad \text{initial feeder network of cluster } C,$$

where c is the central port of cluster C. The capacity of a line $F \in \mathcal{F}^C$ is given by

$$b_f = \min\{b \in \mathcal{B} : b \geq \max(f_{c,h}, f_{h,c})\}.$$

Appendix E.3.2. Reduce feeder capacity

The method to reduce the capacity is performed for each cluster separately. Therefore, we describe the method for a given cluster C. In the algorithm, we will determine and store the difference in profit of reducing the feeder capacity for each feeder service in the cluster separately. Thus, we select one by one the feeder services in the cluster.

Flow over legs.
Let F be the selected feeder line. For this service, we first determine the flow on each leg of the feeder line. Let the legs of the line be given by $l_1, \ldots, l_n$, where n is the number of legs of the service and let the feeder route be given by $p_1, \ldots, p_n, p_1$ (leg l_1 corresponds to the leg between ports p_1 and p_2). Furthermore, let

$$f^o_{p_i} = \sum_{h \in \mathcal{H}} f_{p_i,h}$$

be the total flow with origin port p_i and

$$f^d_{p_i} = \sum_{h \in \mathcal{H}} f_{h,p_i}$$

be the total flow with destination port p_i Then, the flow on leg $1 \leq i \leq n$ is given by

$$f_{l_i} = \sum_{j>i} f^d_{p_j} + \sum_{j \leq i} f^o_{p_j}.$$

Reduce capacity.
Let b_c be the current capacity of the feeder service and b_n the capacity when we reduce this capacity by one size. Then, the reduction needed on leg l_i is equal to

$$y_{l_i} = \max(f_{l_i} - b_n, 0).$$

That is, we only need to reduce the flow over a leg if it is currently larger than the new capacity of the service.

Valid combinations to exchange demand.
The flow over a leg can be reduced by changing the origin and/or destination port of a cargo flow. Since cargo flows between ports are obtained from cargo flows between clusters, there are multiple feasible allocations of the flow to the port pairs. We determine the port combinations between which cargo flows can be exchanged in order to reduce the flow over F.

$\mathcal{L}^o := \{((h_1,h_2),(h_3,h_2)) : h_1 \in F, h_2 \notin C, h_3 \in C \setminus F\}$	combinations with origin in C.
$\mathcal{L}^d := \{((h_1,h_2),(h_1,h_3)) : h_1 \notin C, h_2 \in F, h_3 \in C \setminus F\}$	combinations with destination in C.
$\mathcal{L} := \mathcal{L}^o \cup \mathcal{L}^d$	valid port combinations.

The set $\mathcal{L}$ consists of all valid combinations of port pairs between which cargo can be exchanged to reduce the cargo flow on feeder line F. If $((h_1,h_2),(h_3,h_4)) \in \mathcal{L}$, then the cargo flow over F can be reduced by increasing the satisfied demand between ports h_3 and h_4 and at the same time reducing the demand between ports h_1 and h_2 with the same amount. In this way, the total demand satisfied between clusters does not change as long as ports h_1 and h_3 belong to the same cluster and ports h_2 and h_4 belong to the same cluster. Furthermore, we only want to change the flow over the feeder network in cluster C, so we will add the restriction that the port that does not belong to C is not allowed to be changed. In $\mathcal{L}^o$ the origin port belongs to C and thus we see that the destination port in both port pairs is the same (namely h_2) and, similarly, for $\mathcal{L}^d$ the origin port (h_1) is the same for both pairs. Furthermore, we want to reduce the cargo flow over line F, so we do not want to shift cargo from one leg of service F to another leg. Therefore, we add the restriction that the new port in cluster C is not allowed to be on line F. Thus, port h_3 in the definition of both $\mathcal{L}^o$ and $\mathcal{L}^d$ is an element of $C \setminus F$ (all ports in C that are not visited on line F).

Exchange demand between port pairs.
For each combination $((h_1, h_2), (h_3, h_4))$ of port pairs in $\mathcal{L}$, the revenue decrease per unit of exchanging cargo from the first demand pair to the second is given by $r_{h_1,h_2} - r_{h_3,h_4}$, where $r_{a,b}$ denotes the revenue of satisfying one unit of demand from port a to port b.

Select the combination with the lowest decrease in revenue. We want to exchange as much cargo as possible from the first port pair to the second pair. Clearly, the maximum amount that can be exchanged is bounded by the amount of cargo that is currently transported between the first port pair and the unsatisfied demand between the new port pair. Furthermore, it is bounded by the free capacity of the feeder line over which the new flow has to be transported.

Let p_o denote the port in C of the first port pair, p_n the port in C of the second port pair and p' the port not in C that is part of both port pairs. Furthermore, let $D_{a,b}$ and $D^{sat}_{a,b}$ be the demand and satisfied demand between ports a and b respectively. The demand to be exchanged is bounded by

$$D^{ex}_d = \begin{cases} \min(D^{sat}_{p',p_o}, D_{p',p_n} - D^{sat}_{p',p_n}) & \text{if } p' \text{ is the origin port,} \\ \min(D^{sat}_{p_o,p'}, D_{p_n,p'} - D^{sat}_{p_n,p'}) & \text{if } p' \text{ is the destination port.} \end{cases}$$

Exchanging demand will also change the flow on the feeder lines containing p_o and p_n, but only the flow on the new feeder line is relevant in this case, because this flow will be increased. Let F_n be the new feeder service. The definition of $\mathcal{L}$ guarantees that $F_n \neq F$. If p' is the origin ports of the pairs, then the flow between the port pairs will be on the feeder line for all legs before port p_n, while it will be on the feeder line for all legs after port p_n if p' is the destination ports Let p_n be the k-th port of feeder line F_n and let n the length of the feeder line. Furthermore, let $f^n_{l_i}$ be the flow on feeder line F_n over leg l_i. Then, the amount of cargo that can at most be exchanged is bounded by

$$D^{ex}_f = \begin{cases} \min\limits_{1 \leq i < k} b_{F_n} - f^n_{l_i} & \text{if } p' \text{ is the origin port,} \\ \min\limits_{k \leq i \leq n} b_{F_n} - f^n_{l_i} & \text{if } p' \text{ is the destination port.} \end{cases}$$

Thus, the maximum amount of cargo that can be exchanged between the combinations of port pairs is given by:

$$D^{ex} = \min(D^{ex}_d, D^{ex}_f).$$

The flow over the feeder services has to be updated when we exchange this amount.

Thereto,

$$f^o_{l_i} = \begin{cases} f^o_{l_i} - D^{ex} & 1 \leq i < j \qquad \text{if } p' \text{ is the origin port,} \\ f^o_{l_i} - D^{ex} & j \leq i \leq m \qquad \text{if } p' \text{ is the destination port,} \end{cases}$$

where port p_o is the j-th port on feeder line F and $f^o_{l_i}$ is the flow over leg l_i of feeder line F and m is the length of feeder service F. Similarly,

$$f^n_{l_i} = \begin{cases} f^n_{l_i} + D^{ex} & 1 \leq i < j \qquad \text{if } p' \text{ is the origin port,} \\ f^n_{l_i} + D^{ex} & j \leq i \leq m \qquad \text{if } p' \text{ is the destination port.} \end{cases}$$

The costs of exchanging the demand is given by:

$$C^{ex} = C^{ex} + \begin{cases} (r_{p',p_o} - r_{p',p_n} + c^h_{p_n} - c^h_{p_o})D^{ex} & \text{if } p' \text{ is the origin port,} \\ (r_{p_o,p'} - r_{p_n,p'} + c^h_{p_n} - c^h_{p_o})D^{ex} & \text{if } p' \text{ is the destination port,} \end{cases}$$

where c^h_p is the handling cost per unit in port p and C^{ex} is initialized at 0 each time we consider a new feeder service F.

Next, we can update the reduction needed on each leg and repeat this procedure until either all valid combinations of port pairs are considered or the reduction needed equals zero on each leg. If the capacity of the feeder service can be reduced (the reduction needed equals zero for each leg of the service), then the profit is given by

$$P^{ex} = c^c_{b_c} + c^f_{b_c} - (c^c_{b_n} + c^f_{b_n}) - C^{ex},$$

where c^c_b is the capital and operating costs on the feeder line F when a ship with capacity b is used and c^f_b is the fuel costs on F for a ship with capacity b.

Appendix E.3.3. Exchange port between feeder services

Next, we describe the method to exchange a port between two feeder services. The cargo allocation is not changed in this method, so we can consider the different clusters separately. Thereto, we first select a cluster C. For each combination of two feeder lines in cluster C and each port on the first feeder line, we will consider the increase in profit when we exchange this port from the first service to the second service. Thus, we select two feeder service F_1 and F_2 in C. Furthermore, let q be a noncentral port on feeder line F_1. Then, we will determine at which location it is most profitable to add port q to line F_2 and how large the profit increase is.

Let (p, p') be a consecutive port combination on feeder service F_2. First, determine the cost of the feeder services F_1 and F_2 as they are before we exchange a port:

$$C^{old} = c^c_{b_{f_1}} + c^f_{b_{f_1}} + c^c_{b_{f_2}} + c^f_{b_{f_2}},$$

where b_{f_1} and b_{f_2} are the capacities of F_1 and F_2 respectively and c_b^c and c_b^f are the capital and operating and fuel costs for a ship with capacity b respectively.

Let q now be visited in between ports p and p' on feeder service F_2, that is, remove leg (p, p') from F_2 and add legs (p, q) and (q, p') to F_2. Since q will now be visited on line F_2, we remove it from line F_1. The method described in Section Appendix E.3.2 can be used to determine the new flows on the feeder services F_1 and F_2, because the satisfied demand between port pairs is known. When the flow over each leg is known, the capacity of the feeder service can be determined by:

$$b_f = \min \left\{ b \in \mathcal{B} : b \geq \max_{1 \leq i \leq n} f_{l_i} \right\},$$

where the feeder service is given by $l_1, \ldots, l_n$.

The costs of the feeder services F_1 and F_2 after exchanging port q can again be calculated by:

$$C^{new} = c^c_{b_{f_1}} + c^f_{b_{f_1}} + c^c_{b_{f_2}} + c^f_{b_{f_2}},$$

where b_{f_1} and b_{f_2} are now the new capacities on the feeder lines. The increase in profit is given by:

$$P^q = C^{old} - C^{new}.$$

Repeat this procedure until all consecutive port combinations on F_2 are considered. Then, repeat until all noncentral ports on F_1 are considered.

Appendix E.3.4. Add ports to main routes

In the aggregation phase, we decided to create port clusters in order to reduce the computation time of the cargo-routing model. Central ports of the clusters are visited on the main route network, while all other ports are currently only visited on the feeder network. However, it might be profitable to visit some of those ports on the main network. Ports are clustered based on distance to the central port, so if the central port is visited on a main route, the additional distance that has to be sailed in order to include a noncentral port to the main route will in general be quite small. In this section, we describe a method to add noncentral ports to the main routes.

First, select a main route R and determine the clusters $C_1, \ldots, C_n$ that are visited on R. If a cluster is visited twice on a route, we consider it to be two different clusters. So, a distinction is made between the cluster when it is visited on the eastbound part of the route and the cluster when it is visited on the westbound part of the route. So, each cluster that is visited on a route is unique for the route. Consider a cluster C on route R and let q be a port that belongs to cluster C and is not yet visited on route R, that is, $q \in C \setminus R$. Let (p, p') be a consecutive port combination on main route R, satisfying

$p \in C$ and/or $p' \in C$. Furthermore, let F be the feeder service on which port q is currently visited ($q \in F$).

Cargo reallocation.
Let q now be visited in between ports p and p' on main route R', that is, let $R' = R$ and remove leg (p, p') from R' and add legs (p, q) and (q, p') to R'. Since it is probably not feasible to (un)load all cargo from/to port q on route R (some cargo might be on a different route, or the ship capacity will not suffice to transport all cargo directly via route R), we cannot remove port q from the feeder line F. We want to reallocate as much cargo as possible from feeder service F to main route R, because the handling and transhipment costs will be reduced in this way. The amount of cargo that can be reallocated is first of all restricted by the total amount of cargo from/to port q that is present on the ship. Furthermore, it depends on the unused capacity of the ship on the additional legs. To determine how much cargo can be reallocated according to the unused capacity of the ship, first the position of the inserted port q with respect to the center of the cluster has to be determined.

Two situations can be distinguished: the central port of the cluster is already visited when port q is visited on the main route, or the central port of the cluster has still to be visited when port q is visited. Figure E.1 shows the two possibilities. In the figures, only the central ports of the clusters and port q are considered, but all conclusions that will be drawn, will also hold when more ports are on the route.

Now, consider the left figure, where port q belongs to cluster C and is visited after the central port of the cluster. In the original route, the ship visits first the central port c of cluster C and directly thereafter the central port c' of the cluster C'. Thus, the cargo flows from and to port q are (un)loaded in c. Now, let $f_{c,c'}$ be the flow from port c to port c'. The cargo flow with destination port q will be unloaded in port c, so this flow is not included in flow $f_{c,c'}$. On the other hand, the cargo flow with origin port q is included in flow $f_{c,c'}$, because it is loaded in port c.

When port q is added to the main route after the central port c in the cluster, flows $f_{c,q}$ and $f_{q,c'}$ have to be determined. The difference with the original situation is that the cargo flow from and to port q is now (un)loaded in port q instead of in port c. Thus, the cargo flow to port q is included in flow $f_{c,q}$, while the flow from port q is not included. Combining this with the flows included in flow $f_{c,c'}$, it can be seen that $f_{c,q} = f_{c,c'} - q_f^{out} + q_f^{in}$, where q_f^{in} is the amount of cargo flow unloaded in port q (flow with port q as destination) and q_f^{out} is the amount of cargo flow loaded in port q (flow with origin port q). In flow $f_{q,c'}$ the cargo flow to port q is not included, where the flow from port q is included, so it holds that $f_{q,c'} = f_{c,c'}$. Thus, q_f^{out} is not included in $f_{c,q}$ and included in both $f_{c,c'}$ and $f_{q,c'}$, so all cargo with origin port q on ship route R can be loaded in port q, without exceeding the capacity of the ship. However, the amount of cargo that can be unloaded in port q is bounded by $q_f^{in} \leq b_R - f_{c,c'} + q_f^{out}$, since this cargo is included in the new flow $f_{c,q}$ but not in the old flow $f_{c,c'}$.

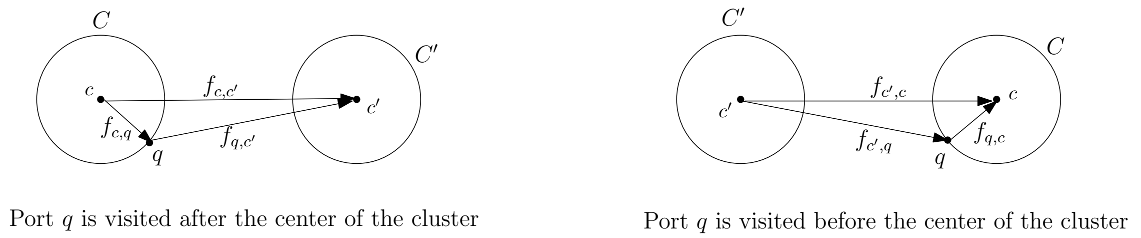

Figure E.1: Example of the positioning of port q with respect to the central port c and c' of the cluster

The other situation is shown in the right figure. In this case, port q belonging to cluster C is visited before the central port c of the cluster. The flow on the initial route between central ports c' and c is denoted by $f_{c',c}$. In this case, the flow to port q is included in flow $f_{c',c}$, while the flow from port q is not included, because it will be loaded in the central port c of cluster C. Now, consider flow $f_{c',q}$ between central port c' and port q. In this flow, the cargo flow to port q is included and the cargo flow from port q is not included. Thus, in this case $f_{c',q} = f_{c',c}$. The cargo flow to port q is now unloaded in port q, so this flow is not included in $f_{q,c}$. However, the flow from port q is already loaded in port q, so is included in $f_{q,c}$. Together with the flows included in $f_{c',c}$, it can be found that $f_{q,c} = f_{c'c} - q_f^{in} + q_f^{out}$, where q_f^{in} and q_f^{out} have the same definitions as above. Now, all cargo to port q can be unloaded without exceeding the capacity of the ship when sailing to port q, but the amount of flow that is loaded is bounded by $q^{out} \leq b_R - f_{c',c} + q_f^{in}$, since this cargo is included in the new flow $f_{q,c}$ but not in the old flow $f_{c',c}$.

The amounts of flow (un)loaded in port q are equal to

$$q^{out} = \min(q_f^{out}, q_s^{out})$$

and

$$q^{in} = \min(q_f^{in}, q_s^{in}),$$

where q_s^{out} and q_s^{in} are the amounts of cargo present on the ship on route R with port q respectively as origin and destination port. Thereafter, the new flows can be determined using the formulas for $f_{a,b}$ given above. Furthermore, q^{in} and q^{out} can be used to update the flows on the feeder service visiting port q by subtracting the flows from the legs over which it should be transported. When no flows are loaded and unloaded anymore in port q on the feeder service, the port can be deleted from the feeder service.

Cost reduction.
Which costs incurred at the main and feeder network are relevant in this method depend on where in the solution algorithm this procedure is executed. When the methods to reduce the feeder network are not yet performed, only the handling costs on the feeder network are considered to be relevant. However, when these methods are already performed also the capital, operating, fuel and port costs of the feeder network are relevant. The handling, port, capital, operating and fuel costs of the main network are relevant in both cases.

The route costs c^r_R and $c^r_{R'}$ consisting of the capital, operating, port visit and fuel costs of the main routes R and R' can be obtained from the method to determine the optimal speed, which is described in Section 3.2.2. The new capacity needed on the feeder route can be obtained from the method described in Section Appendix E.3.2. Thereafter, the new route costs of the feeder route can easily be computed by adding the capital, operating, port visit and fuel costs, because the route duration and speed are fixed. Furthermore, the difference in handling costs can be obtained using q^{in} and q^{out}.

After the cost reduction is determined, repeat this procedure for a new consecutive port combination (p, p') on route R with $p \in C$ and/or $p' \in C$ until as long as they are not all considered yet. Next, repeat until all noncentral ports $q \in C \setminus R$ are considered, all clusters $C \in R$ are considered and finally until all routes R are considered. Then, add the port for which the cost reduction is largest to the main route and at the location where this cost reduction will be obtained. This method is repeated until no cost reduction can be obtained anymore by adding a port to a main route.