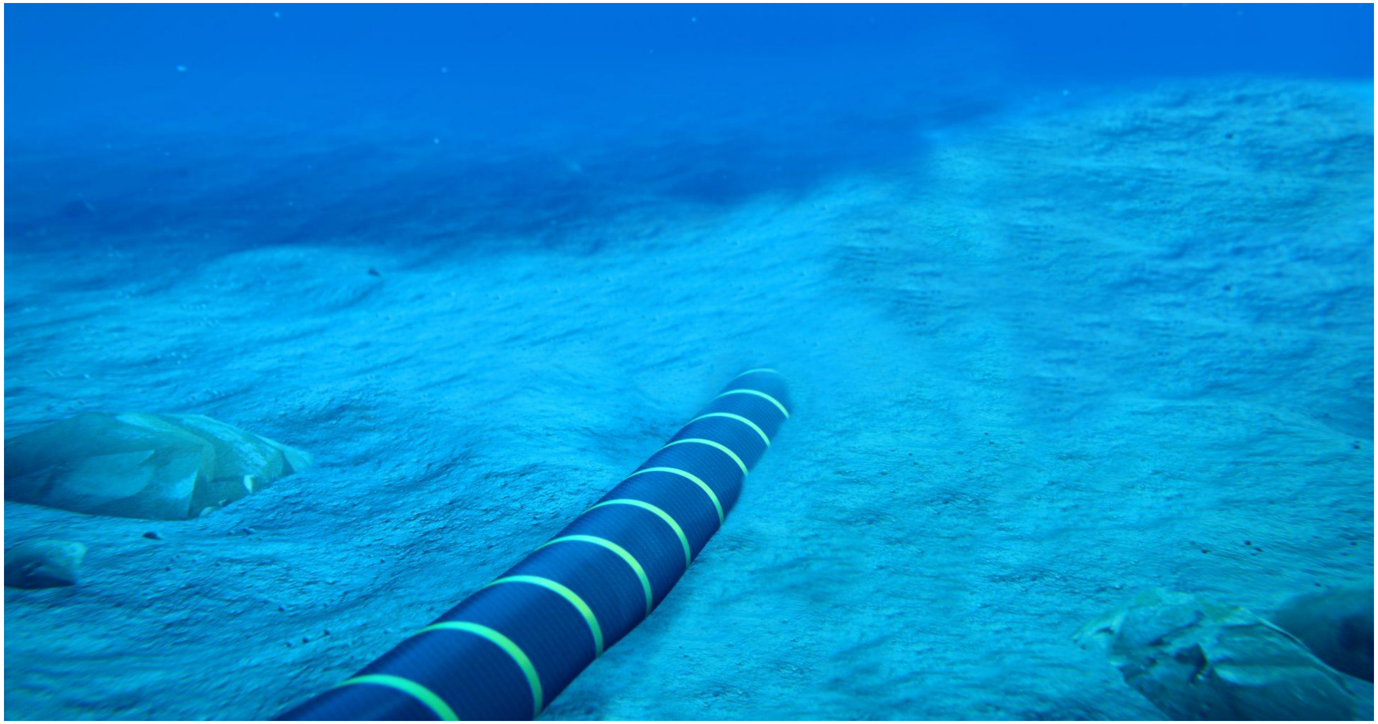
Twelfth SAMO Summer School

Parma, 24-28 June 2024

Ice-breaking *captatio benevolentiae*



A. The longest sea snake existing in nature
B. The portion of a submarine power cable
C. A woman hair shaft after being dyed (500x resolution)

A case study for Global Sensitivity Analysis. From the problem to the solution

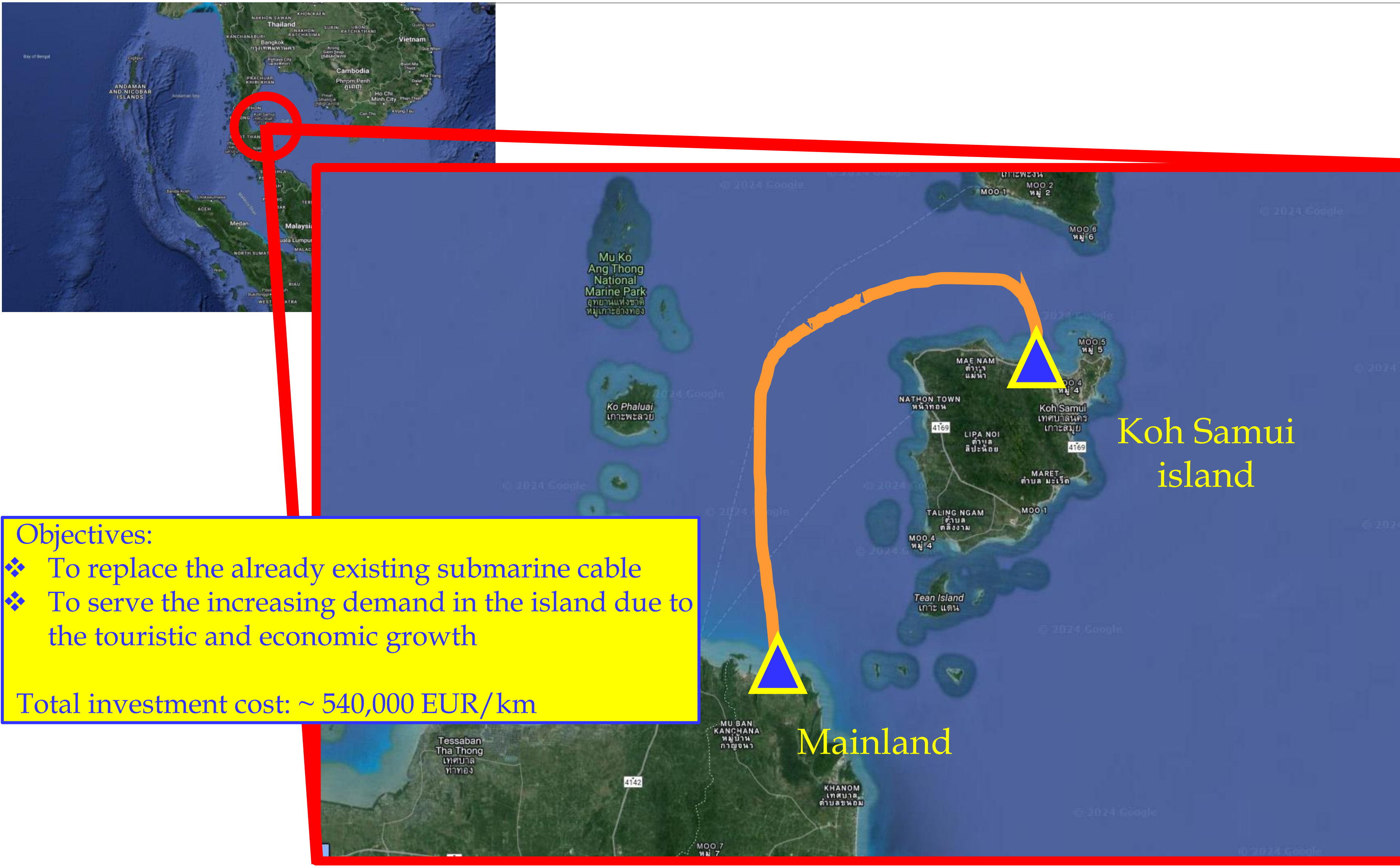
- PART 1: Introduction and description of the case study
- PART 2: Application of Sensitivity Analysis
- PART 3: Sensitivity Analysis for multi-scale models

PART 1: Introduction and description of the case study

PART 2: Application of Sensitivity Analysis

PART 3: Sensitivity Analysis for multi-scale models

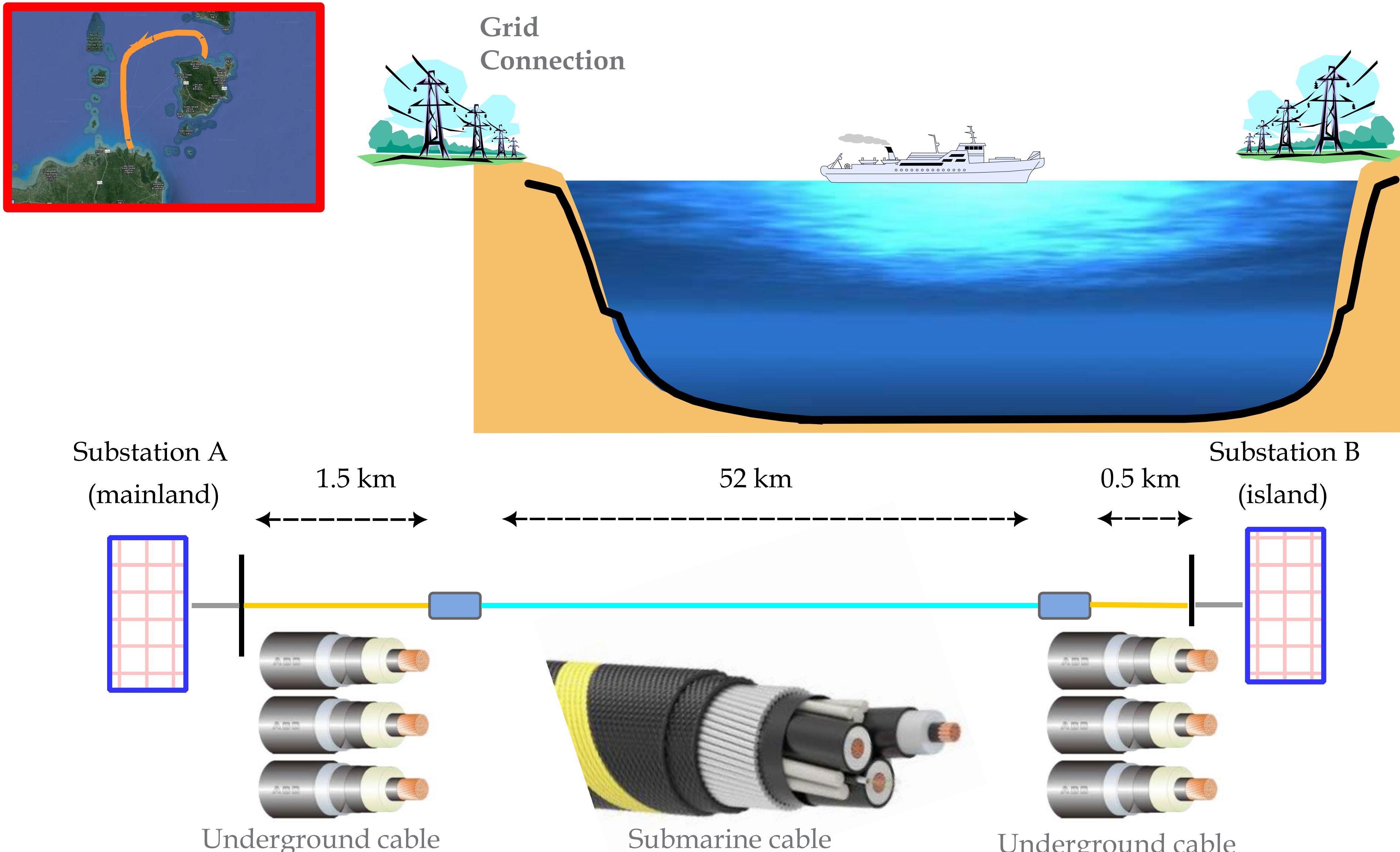
PART 1 – Introduction
Geographical coordinates



Objectives:
- To replace the already existing submarine cable
- To serve the increasing demand in the island due to the touristic and economic growth

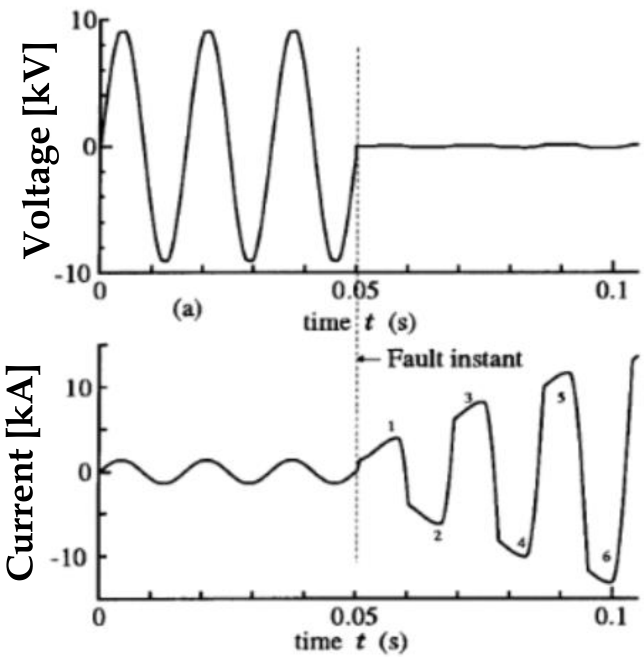
Total investment cost: ~ 540,000 EUR/km

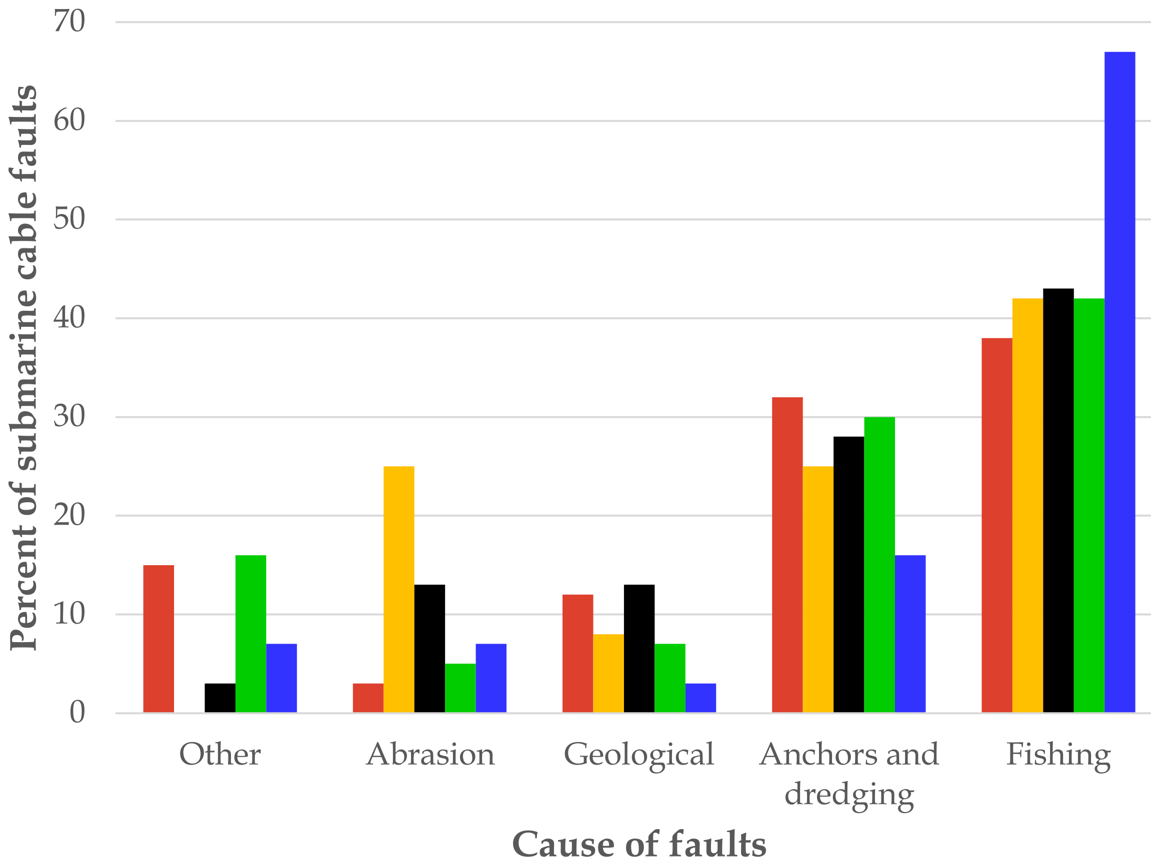
PART 1 – Introduction
The power transmission system under study



Electrical fault: definition and main causes

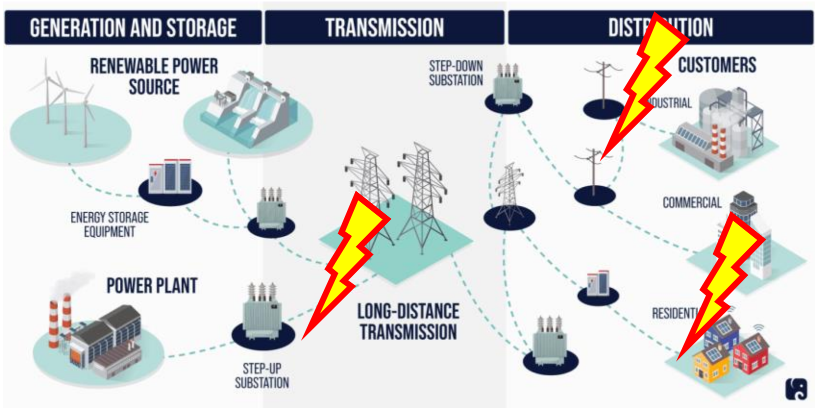
- In nominal conditions, the power system operates at **nominal** current (I) and voltages (V).
- A fault is a condition in which **abnormal** levels of I and V are entered into the power system.
- The excessively high I flowing in the circuit causes **damage** to **equipment and devices**.





Reasons for power system protection

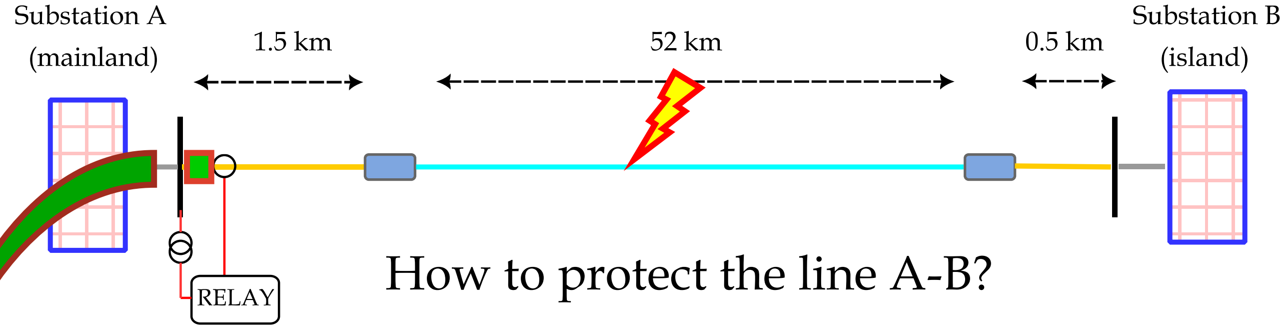
- A *good* power system should ensure the availability of electrical power with no interruptions to every connected customer.



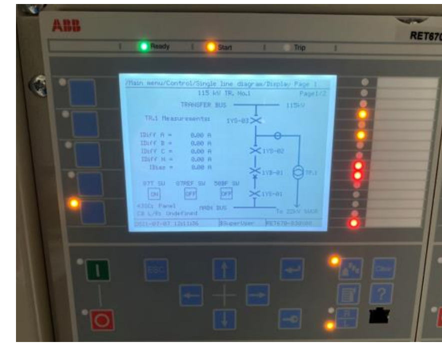
- Faults happen!

- Power system protection does **NOT** prevent the faults. But, it is fundamental to minimize the severity of their impacts, e.g.,:
  - Fires and explosions
  - damage to utility equipment (transformers, cables, etc.)
  - power quality
  - outage costs ↔ system reliability

PART 1 – Introduction
How power system protection works

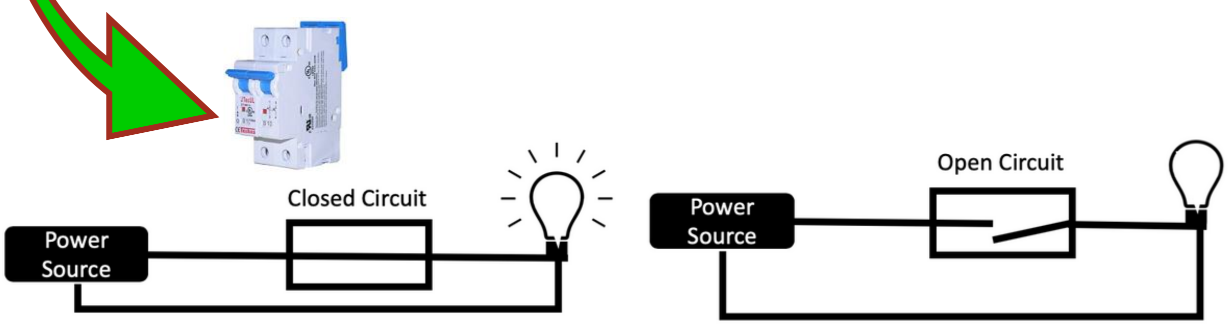


How to protect the line A-B?



- A protective relay is located at the near-end substation.
- It detects the fault and isolates the abnormal part of the power system from the healthy parts with the smallest delay.
- The protective relay is connected to a circuit breaker located at the substation.
- If/when the relays detects the fault, it sends a trip signal

to the circuit breaker which isolates the downstream line.



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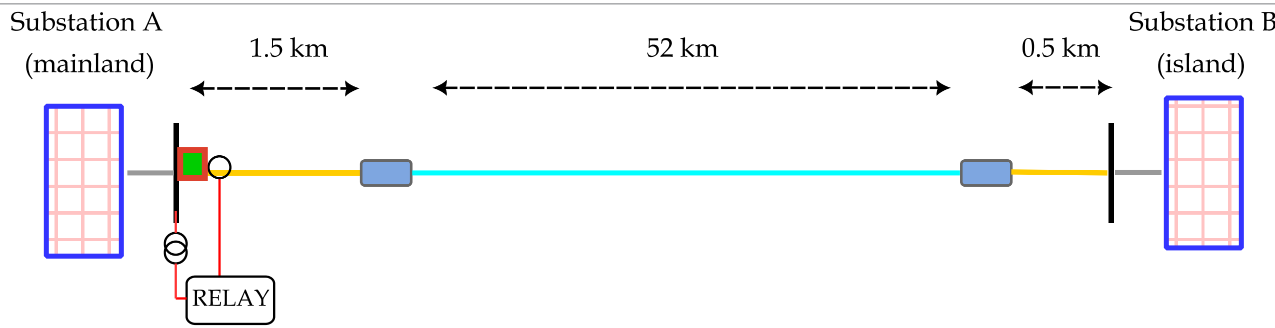
Find the fault to repair it



Voltage transformer

Current transformer

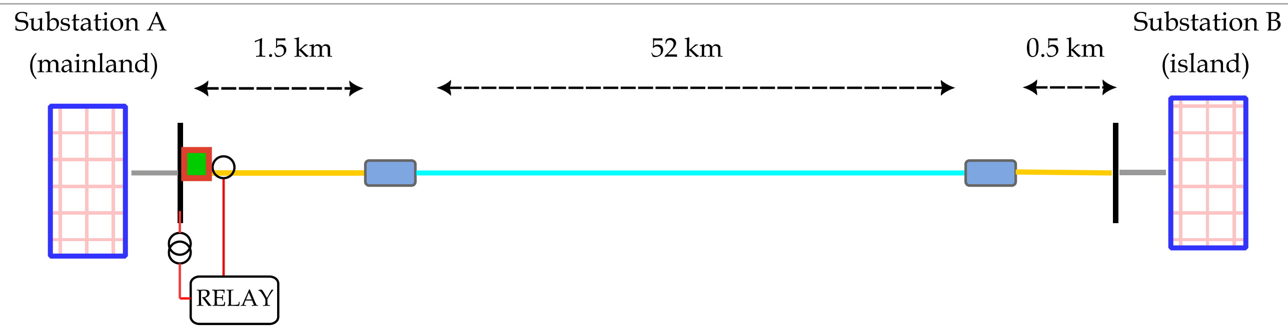
- Once the circuit breaker trips, the line has been protected.
- However, beside the fault isolation, fault has to be *repaired*!
- How to find the distance to the fault? ⟶ Distance relay
- In normal situations, the line is characterized by a *reference* impedance Z_{REF}
- Sensors (VT and CT) are connected to the relay and continuously send *V* and *I*
- The distance relay *measures* the apparent impedance Z_{APP} (between the relay and the fault) starting from *V* and *I*
  - $Z_{APP} \propto V/I$
- The relay compares Z_{APP} with Z_{REF}
- If $Z_{APP} < Z_{REF} \rightarrow$ the relay operates and yields the fault location.

Repairing submarine cables?

- Identify the fault (rough estimate of the fault location)
- Send a Remotely Operated Vehicle (ROV) with fault detection instruments.
- Once the break is located, dispatch a cable ship to repair
- Cable repair ships are loaded with enough cable for repairs (5-10 km); some can send power through the cable to test it before install (breaks are not uncommon)
- In shallow water, scuba-divers can operate to repair the cable (sometimes hard to find due to displacement)
- In deep water, the ship grabs the cable and drags it to the surface. After the cable is retrieved and on board, engineers repair the cable in a repair room

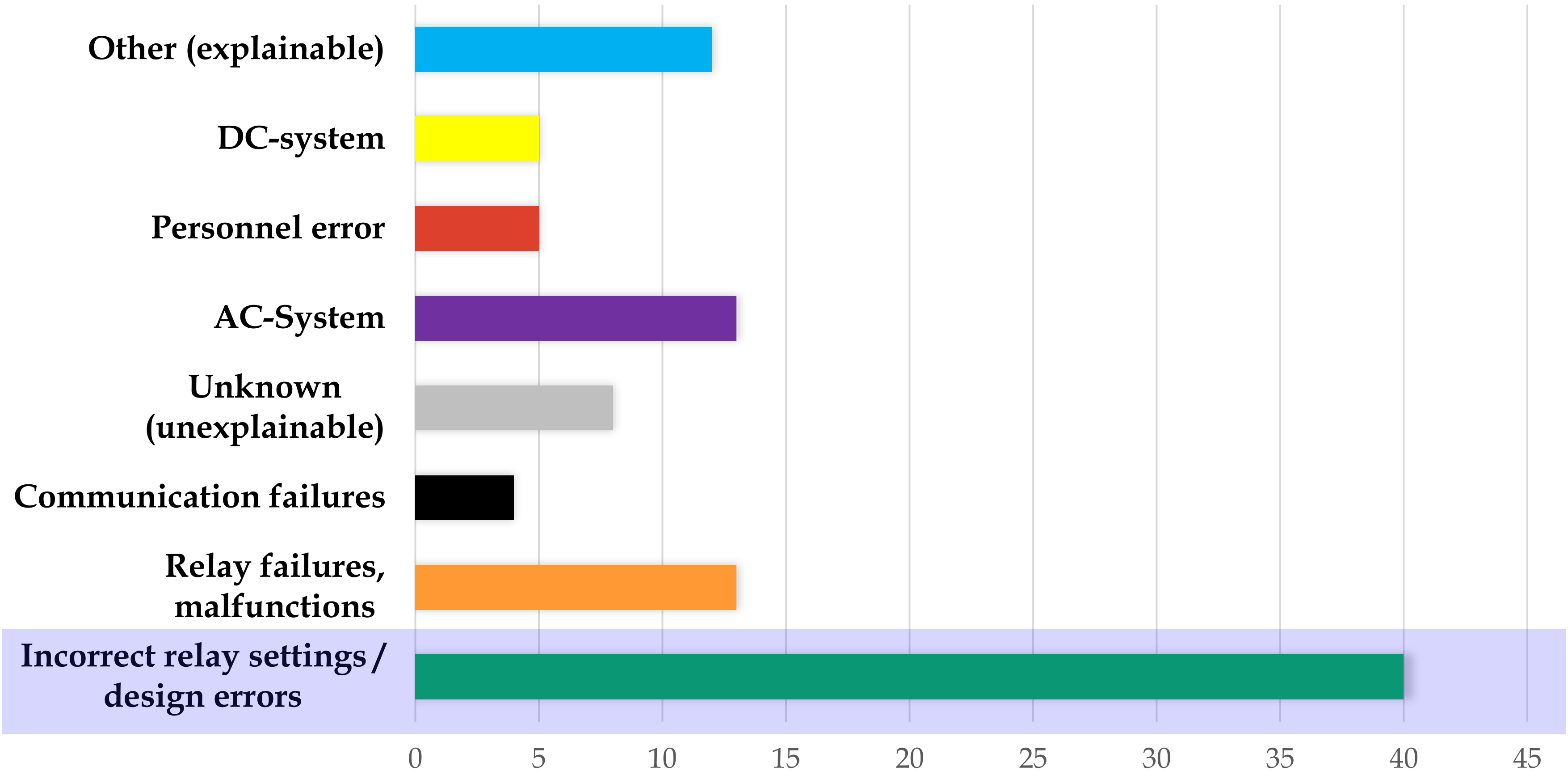
- Total time ≈ time to travel + time to repair

PART 1 – Introduction
The triggering event



- One day, a fault happened, and the relay operated but…
- …the fault was recorded quite wrong!
- Total time ≈ time to travel **+ time to find +** time to repair
- Few consequences:
  - De-energization of the line downstream the relay
  - Load rotation for the customers of Koh Samui
  - mobile diesel generators to be placed on Koh Samui to ensure a (small) power supply, fuel and the workers during the weeks of power interruption
  - Outage costs for the system operator
    - power not-sold
    - compensation for the customers

- Why did the relay misoperate?



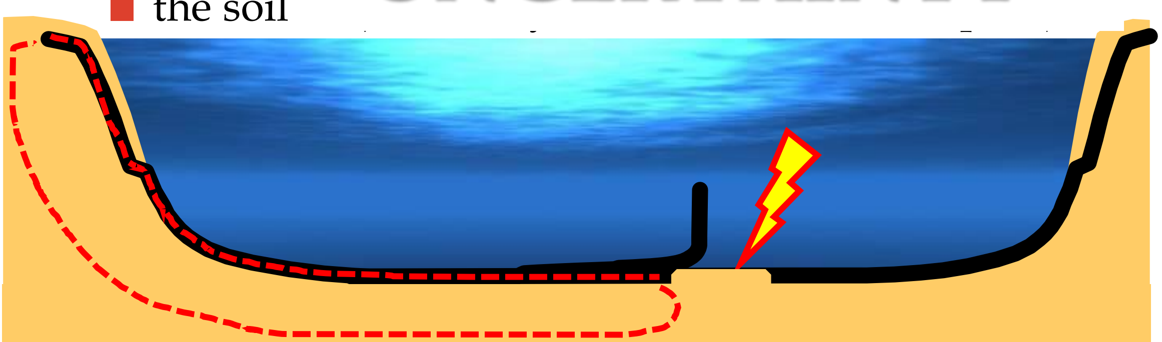
Tracing back the causes

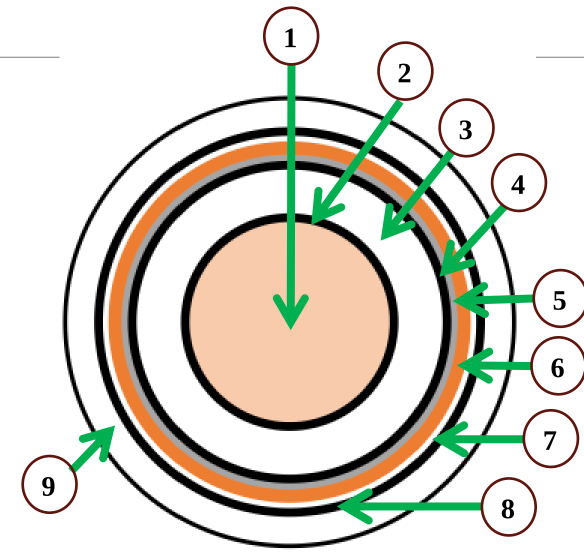
- Why did the relay misoperate?
- Remember that
  - $\boxed{Z_{APP}} < \boxed{Z_{REF}}$ → the relay operates and records the fault location f (Z_{APP}, Z_{REF})

$Z_{APP} = f(V, I, \boxed{k_0})$

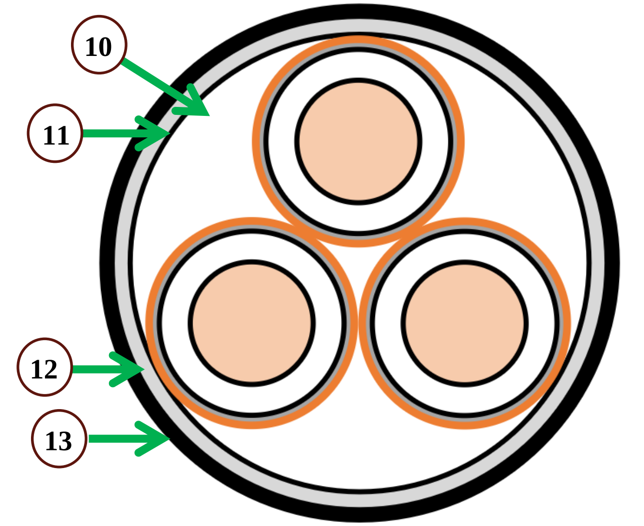
- Relay setting
  - Z_0 = Zero-sequence impedance of the line
  - Z_1 = Positive-sequence impedance of the line
- Z_0 and Z_1 are computed from *nominal* parameters of
  - the cable
  - the soil

UNCERTAINTY





Cross-section of underground and submarine cable (top and bottom)



PART 1: Introduction and description of the case study

PART 2: Application of Sensitivity Analysis

PART 3: Sensitivity Analysis for multi-scale models

1. Define the purpose of the analysis
2. Identify the model
3. Identify the output
4. Identify the inputs
5. Characterize the inputs‘ uncertainty
6. Choose the Sensitivity Analysis method
7. Generate the input samples
8. Evaluate the model
9. Estimate the output uncertainty / Extract the sensitivity indices
10. Interpret the results
11. Complement Sensitivity Analysis with graphical tools
12. Iterate the analysis if needed

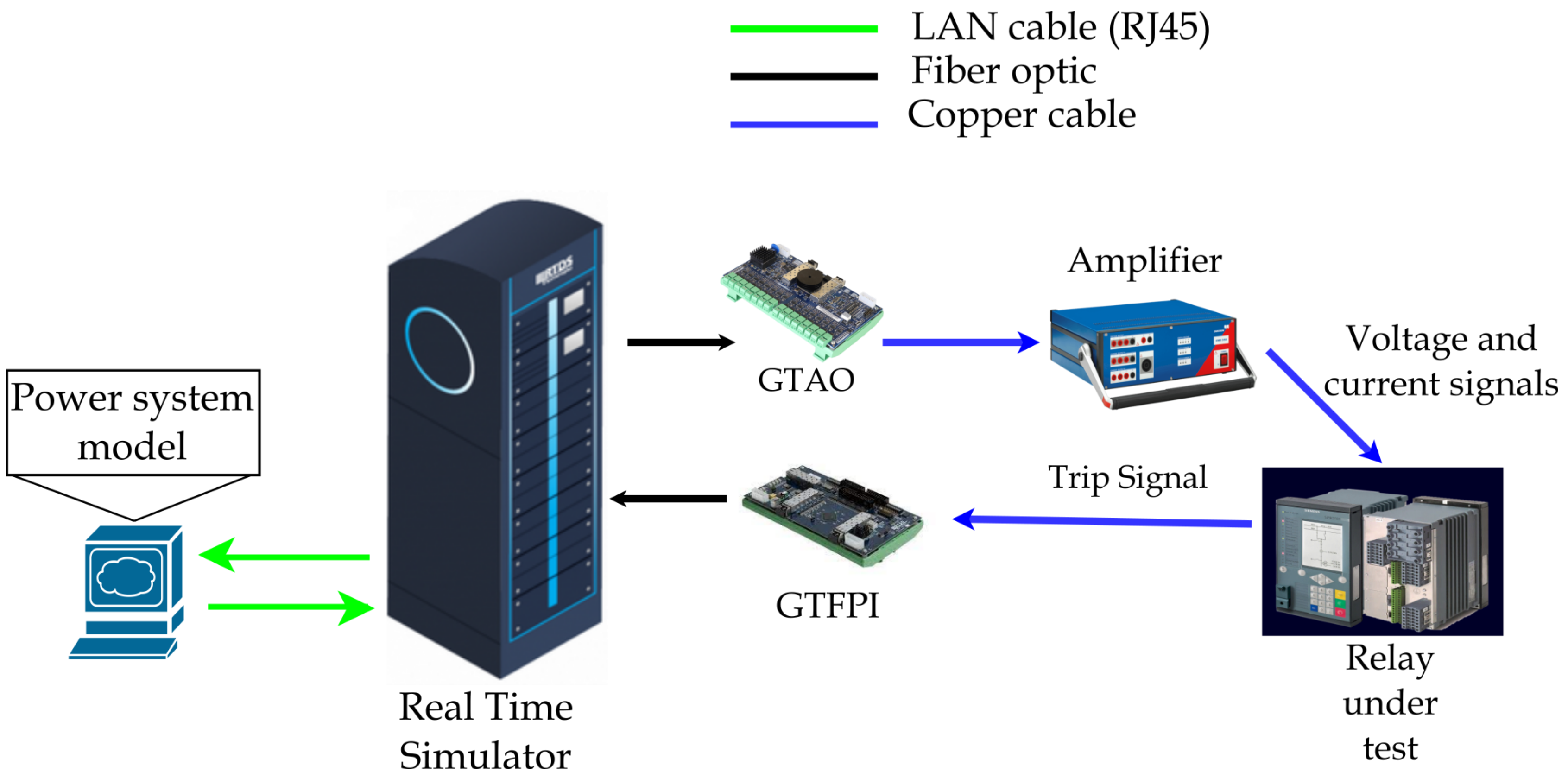
Step 1. Define the purpose of the analysis

- Where did the relay misoperation come from?
- How do improper relay settings affect the relay performance?

1. Which of the uncertainty sources contribute to the relay performance the most?
2. Do any of the uncertainty sources have a negligible impact on the relay performance?
3. Do certain modeling choices affect the relay performance?

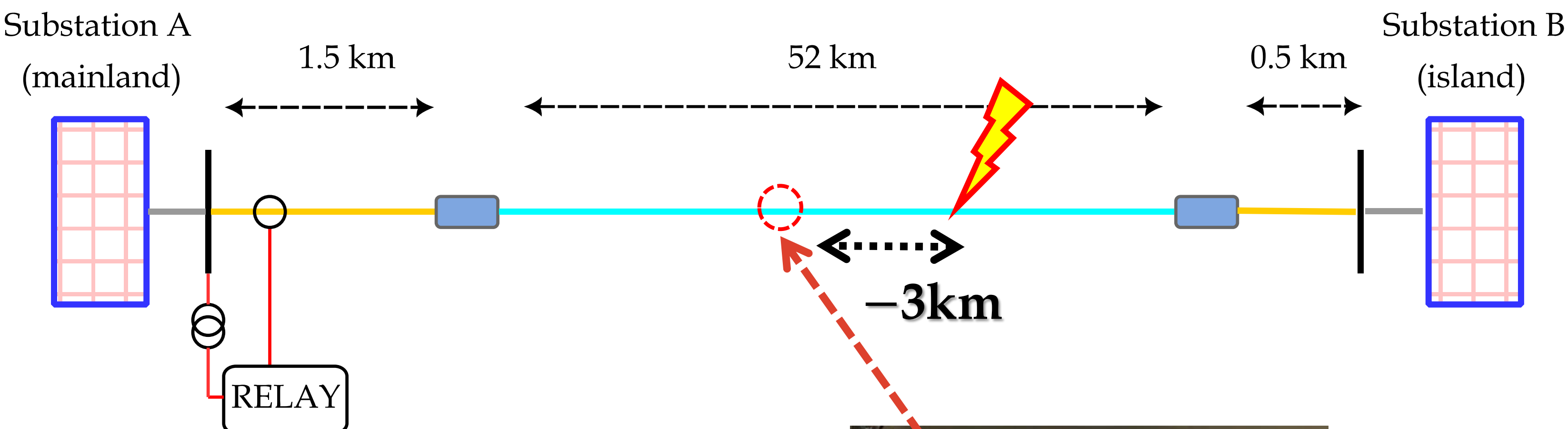
Step 2. Identify the model

- Adopt a simulation model to performs fault analysis



Step 3. Identify the output

- To quantify the relay performance, the error in the fault location is used
  - Error = recorded Fault Location – true Fault Location



- $\varepsilon = FL_{REC} - FL_{TRUE}$

FL_{TRUE}	FL_{REC}	ε
30 km	27 km	−3km

Step 4. Identify the inputs

- Error = f (**u**)
- **u** = $[u_1, \ldots, u_{34}]$
  - Cable geometrical data
  - Cable cross-section data
  - Earth resistivity
- Fault location at 30 km, "perfect" *I* and *V*

	Name	Description	Units	Nominal value
Land cable (UG_1–UG_2)	u_1, u_{23}	Radius of the conductor	mm	17
	u_2, u_{24}	Thickness of the conductor screen layer	mm	1.5
	u_3, u_{25}	Thickness of the cross-linked polyethylene (XLPE) insulation layer	mm	16
	u_4, u_{26}	Thickness of the XLPE insulation screen layer	mm	1.5
	u_5, u_{27}	Thickness of the lead sheath	mm	3.5
	u_6, u_{28}	Earth resistivity (dry inland soil)	Ωm	–
	u_7, u_{29}	x_1 coordinate of the cable	m	-0.5
	u_8, u_{30}	x_2 coordinate of the cable	m	0
	u_9, u_{31}	x_3 coordinate of the cable	m	0.5
	u_{10}, u_{32}	y_1 coordinate of the cable	m	0.75
	u_{11}, u_{33}	y_2 coordinate of the cable	m	0.75
	u_{12}, u_{34}	y_3 coordinate of the cable	m	0.75
Submarine cable	u_{13}	Radius of the conductor	mm	13.25
	u_{14}	Thickness of the conductor screen layer	mm	2
	u_{15}	Thickness of the insulation layer	mm	15
	u_{16}	Thickness of the XLPE insulation screen layer	mm	1.5
	u_{17}	Thickness of the lead sheath	mm	2.1
	u_{18}	Thickness of the semiconducting PE	mm	2
	u_{19}	Thickness of the armour bedding	mm	1.5
	u_{20}	Thickness of the armour	mm	6
	u_{21}	Thickness of the outer serving	mm	4.5
	u_{22}	Earth resistivity (sand with seawater)	Ωm	–

Step 5. Characterize the inputs' uncertainty

- Probability Density Functions (PDFs) for the uncertainty of the inputs
  - Cable geometrical data → Displacement after the field installation
  - Cable cross-section data → Tolerance from cable manufacturers
  - Earth resistivity → Variability/randomness

	Name	Description	Units	Nominal value	Range
Land cable (UG_1–UG_2)	u_1, u_{23}	Radius of the conductor	mm	17	[16.15, 17.85]
	u_2, u_{24}	Thickness of the conductor screen layer	mm	1.5	[1.425, 1.575]
	u_3, u_{25}	Thickness of the cross-linked polyethylene (XLPE) insulation layer	mm	16	[15.2, 16.8]
	u_4, u_{26}	Thickness of the XLPE insulation screen layer	mm	1.5	[1.425, 1.575]
	u_5, u_{27}	Thickness of the lead sheath	mm	3.5	[3.325, 3.675]
	u_6, u_{28}	Earth resistivity (dry inland soil)	Ωm	–	[20, 1000]
	u_7, u_{29}	x_1 coordinate of the cable	m	-0.5	[-0.475,-0.525]
	u_8, u_{30}	x_2 coordinate of the cable	m	0	[-0.05, 0.05]
	u_9, u_{31}	x_3 coordinate of the cable	m	0.5	[0.475, 0.525]
	u_{10}, u_{32}	y_1 coordinate of the cable	m	0.75	[0.5, 1]
	u_{11}, u_{33}	y_2 coordinate of the cable	m	0.75	[0.5, 1]
	u_{12}, u_{34}	y_3 coordinate of the cable	m	0.75	[0.5, 1]
Submarine cable	u_{13}	Radius of the conductor	mm	13.25	[12.59, 13.91]
	u_{14}	Thickness of the conductor screen layer	mm	2	[1.9, 2.1]
	u_{15}	Thickness of the insulation layer	mm	15	[14.25, 15.75]
	u_{16}	Thickness of the XLPE insulation screen layer	mm	1.5	[1.425, 1.575]
	u_{17}	Thickness of the lead sheath	mm	2.1	[1.995, 2.205]
	u_{18}	Thickness of the semiconducting PE	mm	2	[1.9, 2.1]
	u_{19}	Thickness of the armour bedding	mm	1.5	[1.425, 1.575]
	u_{20}	Thickness of the armour	mm	6	[5.7, 6.3]
	u_{21}	Thickness of the outer serving	mm	4.5	[4.275, 4.725]
	u_{22}	Earth resistivity (sand with seawater)	Ωm	–	[0, 500]

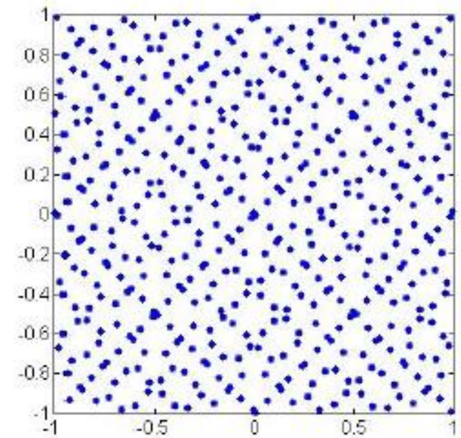
Step 6. Choose the SA method

- Variance-based SA
- BSPCE to compute Variance-based Sensitivity Indices

PART 2 – Application of Sensitivity Analysis

Step 7. Generate the input matrix

- Sampling strategy: Quasi-random Sobol
- Sample size N = 1024



- Generate the input matrix

u_1 u_2 u_3 … Inputs u_{34}

Samples

1	16.3654	1.4960	16.6099	1.4313	3.3439	559.1927	-0.5060	-0.0024	0.5164	1.3488	1.2313	0.9350	9.6356	2.0183	15.3784	1.4610	2.0891	1.9752	1.5160	5.9665	4.6307	189.1882
2	17.2914	1.5311	15.6310	1.5648	3.5953	445.0905	-0.4909	0.0390	0.4827	0.9709	0.6731	1.4983	8.7910	1.9653	14.9990	1.5702	2.1663	2.0107	1.4300	6.2346	4.3591	416.8220
3	16.9267	1.5708	16.3316	1.5010	3.4698	126.4021	-0.5210	0.0228	0.4981	1.2431	0.7647	0.6568	9.0450	2.0570	14.5216	1.4896	2.0036	2.0984	1.5384	6.0564	4.5175	321.8352
4	17.8460	1.4560	15.3027	1.4847	3.5459	969.7573	-0.4822	-0.0375	0.5010	0.6249	1.3306	1.2223	9.3293	1.9094	15.1002	1.5214	2.1336	1.9129	1.4732	5.7322	4.4653	34.0836
5	16.2893	1.5037	15.4236	1.5225	3.6697	676.8663	-0.5171	-0.0399	0.4930	0.8489	0.6218	1.0367	9.1870	2.0343	15.2537	1.4796	2.1093	2.0322	1.5248	5.8851	4.2865	116.0187
6	17.2086	1.4686	16.0416	1.4639	3.3964	296.6422	-0.4797	0.0014	0.5092	1.4710	1.0324	0.6003	9.2413	1.9868	14.3674	1.5139	2.0288	1.9537	1.4589	6.2141	4.6744	278.9476
7	16.5783	1.4294	15.9461	1.4514	3.5330	251.6648	-0.5067	0.0353	0.5247	0.7427	1.4057	1.3051	9.4936	2.0909	14.6572	1.4333	2.1947	1.9414	1.5662	6.0922	4.3965	498.9937
8	17.5042	1.5444	16.5140	1.5429	3.4350	874.9703	-0.4964	-0.0250	0.4776	1.1246	0.9403	0.8704	8.8790	1.9380	15.7193	1.5404	2.0615	2.0699	1.4832	5.8194	4.5574	146.0642
9	16.4989	1.5539	15.8689	1.4954	3.3884	596.9942	-0.5134	0.0441	0.4963	0.7924	1.1470	0.8102	9.2953	1.9529	15.0447	1.5311	2.1460	2.0385	1.5303	6.1297	4.5533	181.5656
10	17.4191	1.4389	16.4900	1.5164	3.6398	469.4973	-0.4773	-0.0084	0.5062	1.4183	0.6984	1.3735	9.1339	2.0057	14.5833	1.4999	2.0166	1.9725	1.4438	5.7820	4.4929	455.5883
11	16.7878	1.4778	15.5976	1.5676	3.4267	26.3897	-0.5097	-0.0300	0.5154	0.6783	0.8645	0.5315	8.9388	1.9220	14.8677	1.5599	2.1526	1.9351	1.5616	5.9226	4.6650	298.6831
12	17.7146	1.5130	16.1687	1.4387	3.5028	886.9752	-0.4997	0.0161	0.4871	1.0485	1.2899	1.0971	9.4311	2.0694	15.5049	1.4513	2.0757	2.0512	1.4969	6.1766	4.3741	88.5623
13	16.1501	1.4465	16.2583	1.5498	3.6308	701.2694	-0.5026	0.0066	0.5197	1.2921	0.5067	1.1615	8.8544	1.9994	15.6356	1.5500	2.0491	1.9940	1.5016	6.0190	4.4203	14.2642
14	17.0769	1.5613	15.2763	1.4536	3.3576	334.4475	-0.4880	-0.0459	0.4796	0.9182	1.0893	0.7251	9.5767	2.0467	14.7377	1.4436	2.1817	2.0170	1.4352	5.7696	4.5969	349.5586
15	16.7112	1.5219	16.7863	1.4810	3.5814	168.8790	-0.5235	-0.0175	0.4889	1.1787	1.4738	1.4304	9.3797	1.9256	14.2658	1.5037	2.0424	2.0797	1.5518	5.9290	4.3052	381.5267
16	17.6314	1.4868	15.7542	1.5349	3.4835	774.9616	-0.4858	0.0286	0.5105	0.5487	0.9304	0.9957	8.9883	2.0783	15.3629	1.4699	2.1227	1.9066	1.4694	6.2721	4.7049	232.2045
17	16.4352	1.5344	16.0659	1.4579	3.4149	961.3571	-0.4765	-0.0338	0.5132	0.5198	1.4537	1.0177	8.8906	1.9891	14.8275	1.4926	2.1267	1.9644	1.5749	6.2503	4.6261	336.0776
18	17.2217	1.4945	15.4995	1.5540	3.5132	105.0147	-0.5142	0.0199	0.4845	1.1439	0.8877	0.5793	9.5412	2.0429	15.5497	1.5338	1.9974	2.0499	1.4885	5.9986	4.3348	50.0996
19	16.9898	1.4597	16.5880	1.5301	3.3769	398.8203	-0.4974	0.0417	0.4940	0.8844	0.5502	1.2656	9.2152	1.9356	15.0724	1.4439	2.1727	2.0624	1.5219	5.7080	4.5073	203.1901
20	17.7829	1.5700	15.9715	1.4762	3.6499	514.4253	-0.5121	-0.0060	0.5036	1.2642	1.1082	0.8250	9.1538	2.0823	14.5494	1.5624	2.0958	1.9268	1.4571	6.0534	4.4466	433.0787
21	16.3524	1.4660	15.6553	1.5122	3.5659	826.4271	-0.4903	-0.0213	0.4898	1.0198	0.8134	0.8857	9.3608	1.9614	14.3044	1.4362	2.0684	2.0214	1.5461	6.2004	4.2950	483.7176
22	17.1456	1.5058	16.6858	1.4911	3.4895	209.4096	-0.5002	0.0325	0.5110	0.6437	1.2787	1.4471	9.0693	2.0081	15.3166	1.5526	2.2010	1.9929	1.4795	5.8504	4.6949	129.1285
23	16.6480	1.5399	15.3766	1.4436	3.6149	286.9261	-0.4865	0.0042	0.5206	1.3847	1.1594	0.6475	8.7451	1.9133	15.6065	1.4626	2.0224	1.9054	1.5118	5.8410	4.4030	100.9752
24	17.4345	1.4298	16.3571	1.5724	3.3639	657.0340	-0.5228	-0.0435	0.4802	0.7646	0.7487	1.2072	9.6257	2.0671	14.7701	1.5064	2.1026	2.0839	1.4295	6.0974	4.5799	261.7795
25	16.5620	1.4393	15.2006	1.4687	3.4595	936.9540	-0.4933	0.0126	0.4991	1.0881	1.4168	1.1434	9.0073	2.0303	14.4705	1.5721	2.0821	2.0027	1.5511	5.8035	4.5345	281.6864
26	17.3559	1.5494	16.2342	1.5273	3.5577	67.2093	-0.5037	-0.0273	0.5017	0.7160	0.9915	0.7051	9.4202	1.9767	15.1575	1.4542	2.1593	1.9866	1.4654	6.1348	4.4827	73.3473

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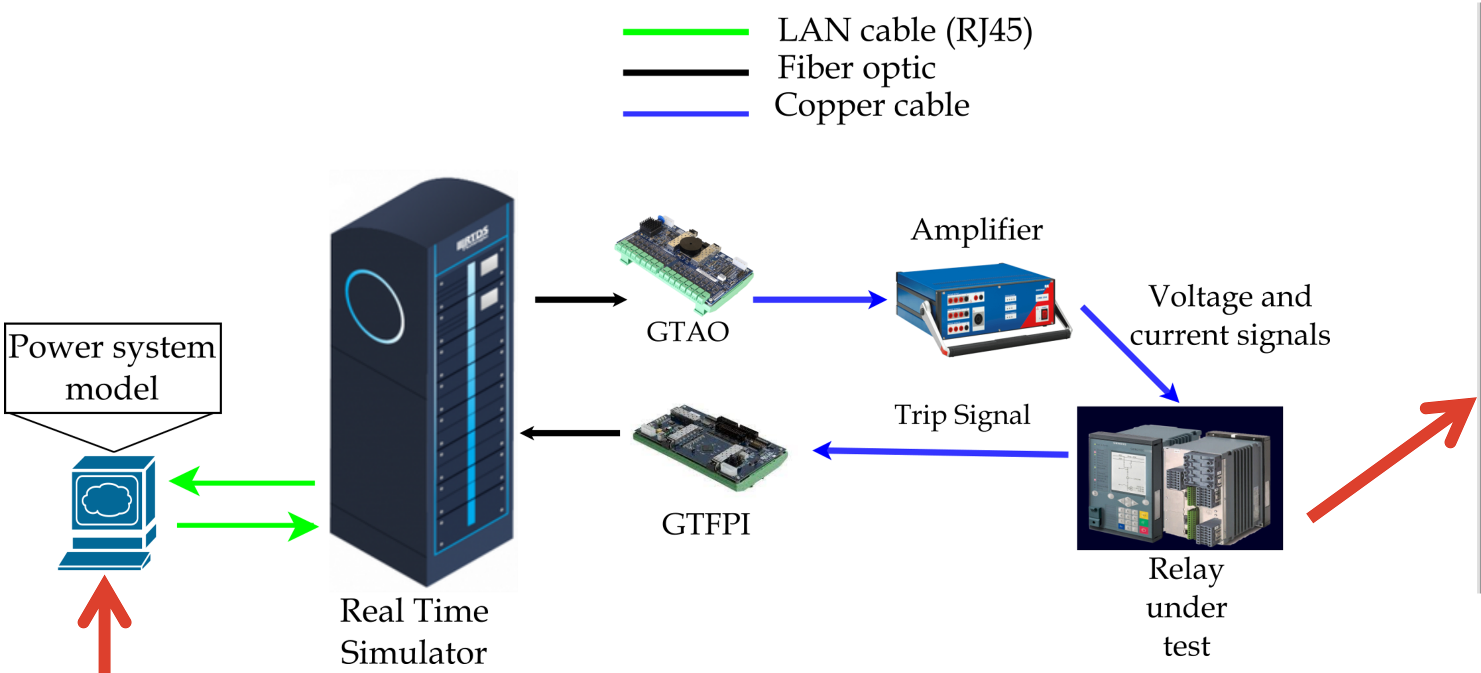
Step 8. Evaluate the model

- Perform the simulations with the Input Matrix

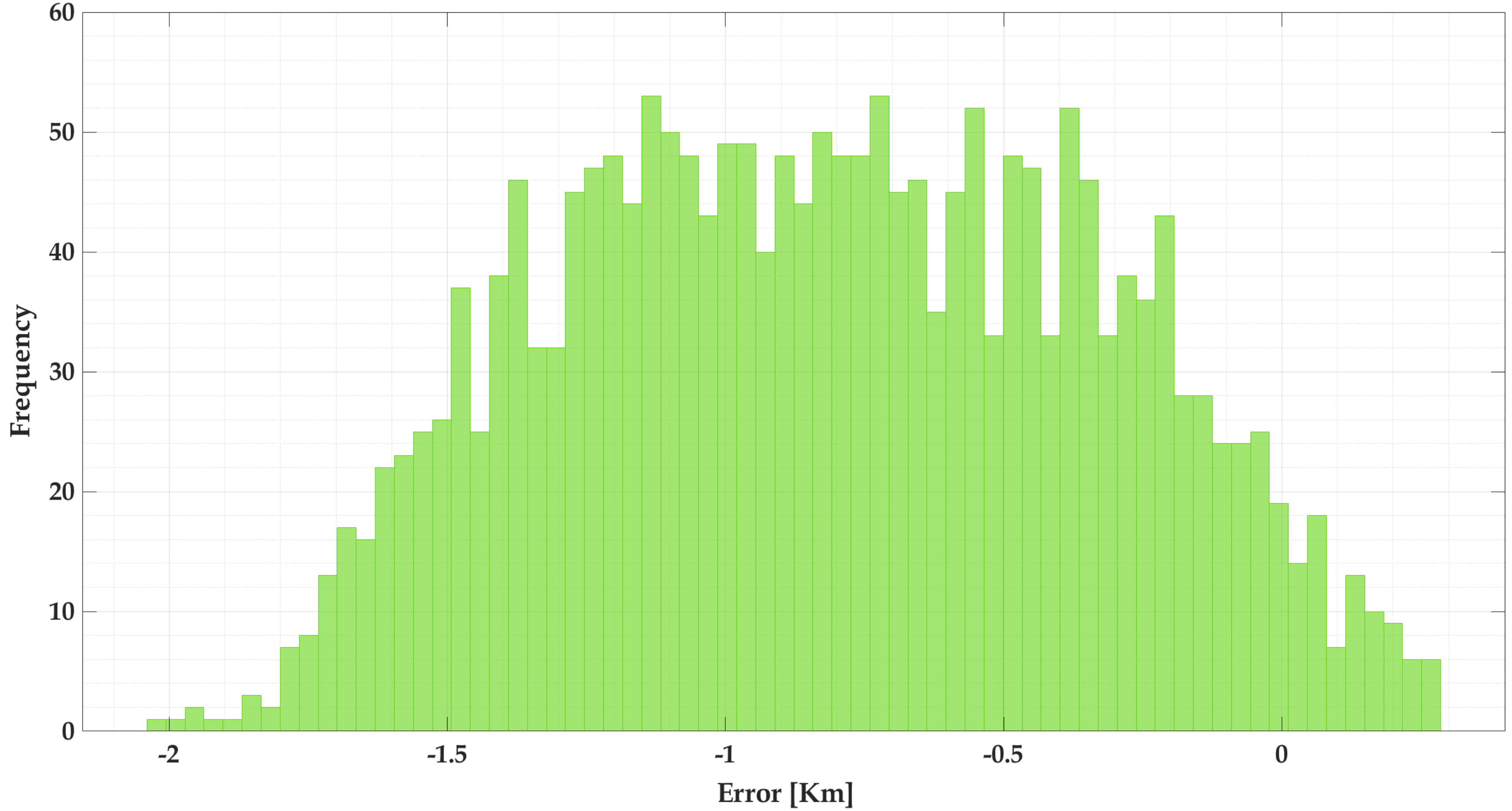
$$\varepsilon = FL_{REC} - FL_{TRUE}$$



Input Matrix

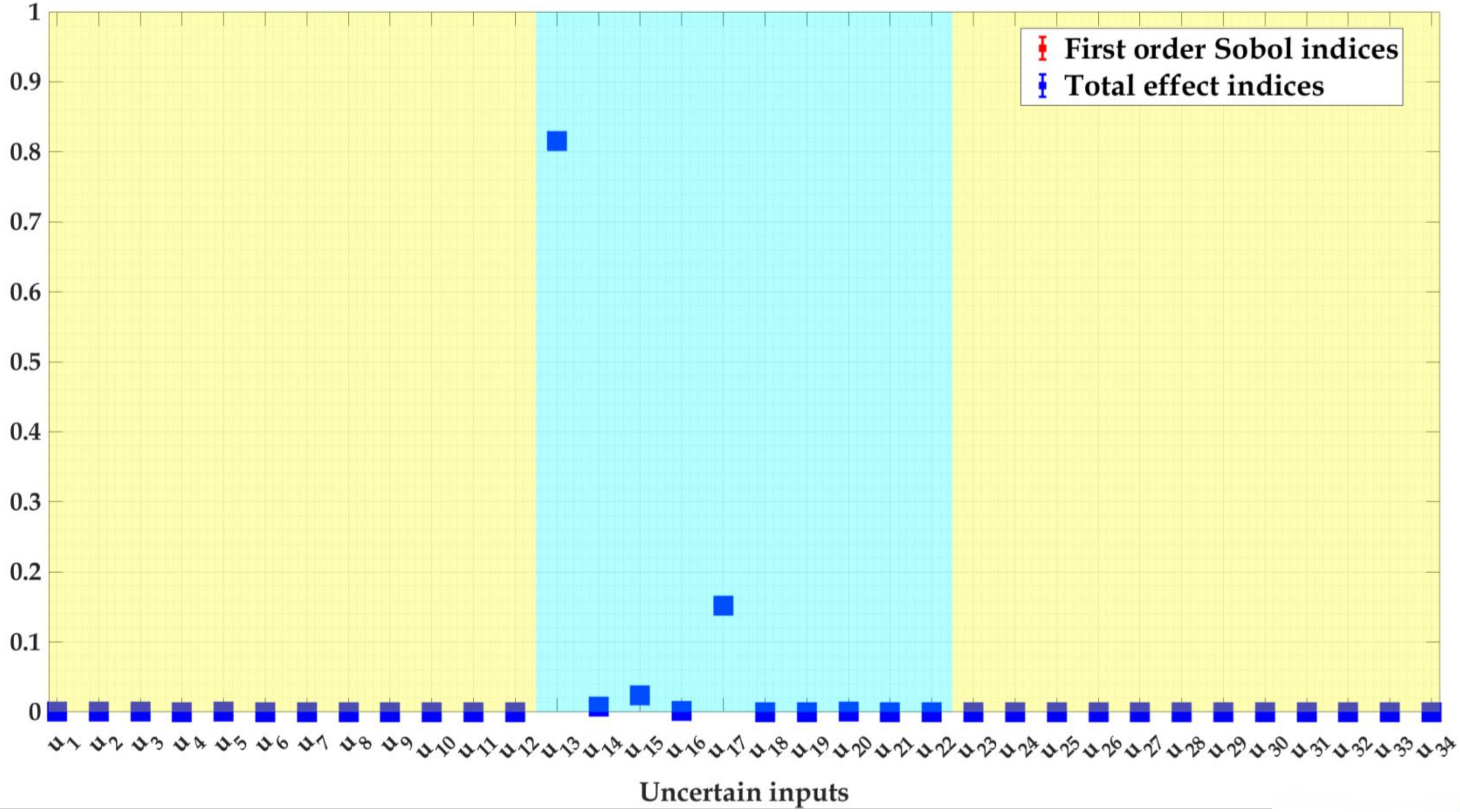
	1
1	-0.6945
2	-0.5597
3	-0.6354
4	-0.5851
5	-0.6938
6	-0.4852
7	-0.5007
8	-0.7574
9	-0.6283
10	-0.6445
11	-0.5226
12	-0.5870
13	-0.6191
14	-0.4138
15	-0.5220
16	-0.9979
17	-0.5531
18	-0.5604
19	-0.8026
20	-0.6410
21	-0.5645
22	-0.8329
23	-0.6754
24	-0.4180
25	-0.5972
26	-0.6543

PART 2 – Application of Sensitivity Analysis
Step 9a. Estimate the output uncertainty



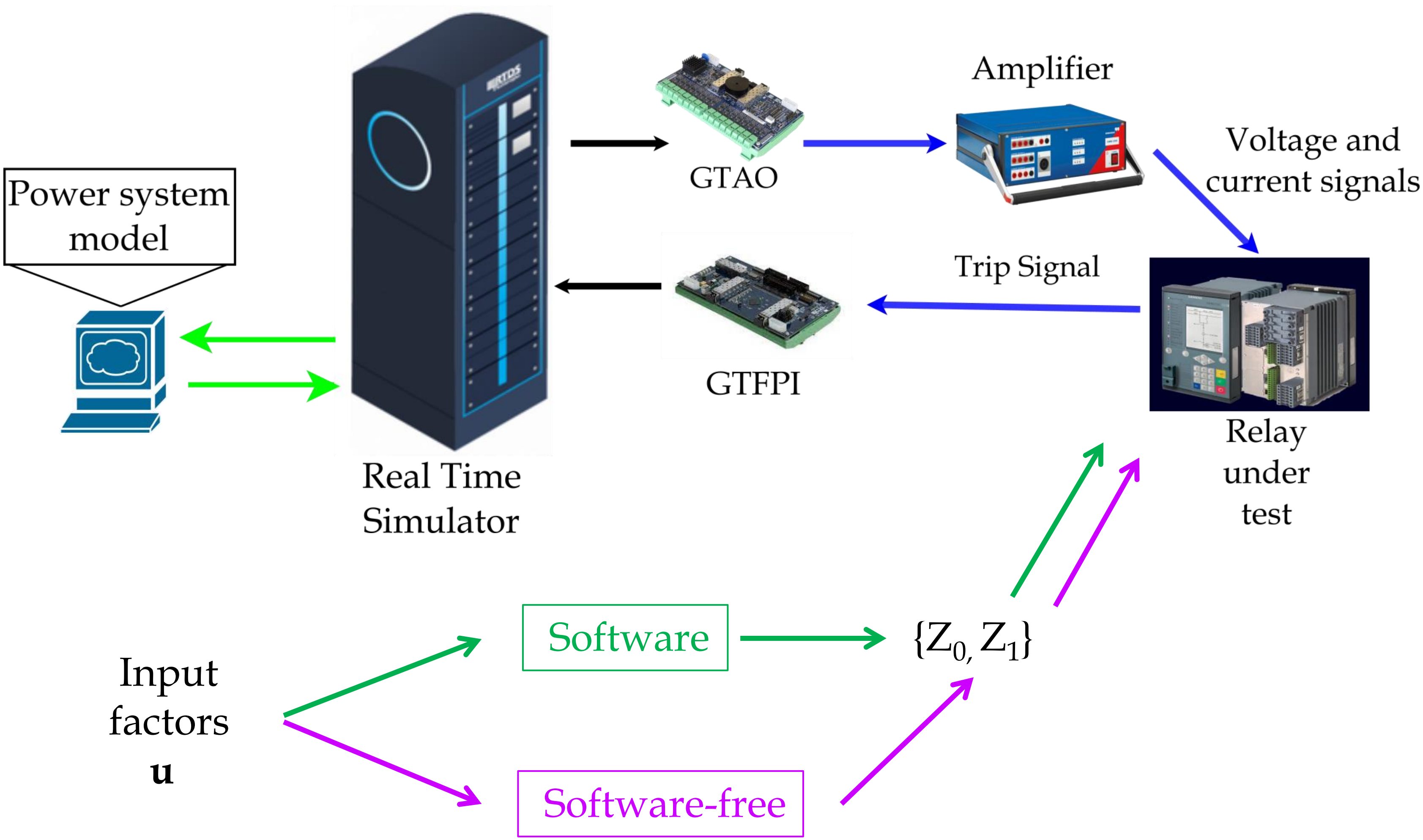
- The relay can make an error up to 2 km!!

Step 9b. Extract the sensitivity indices



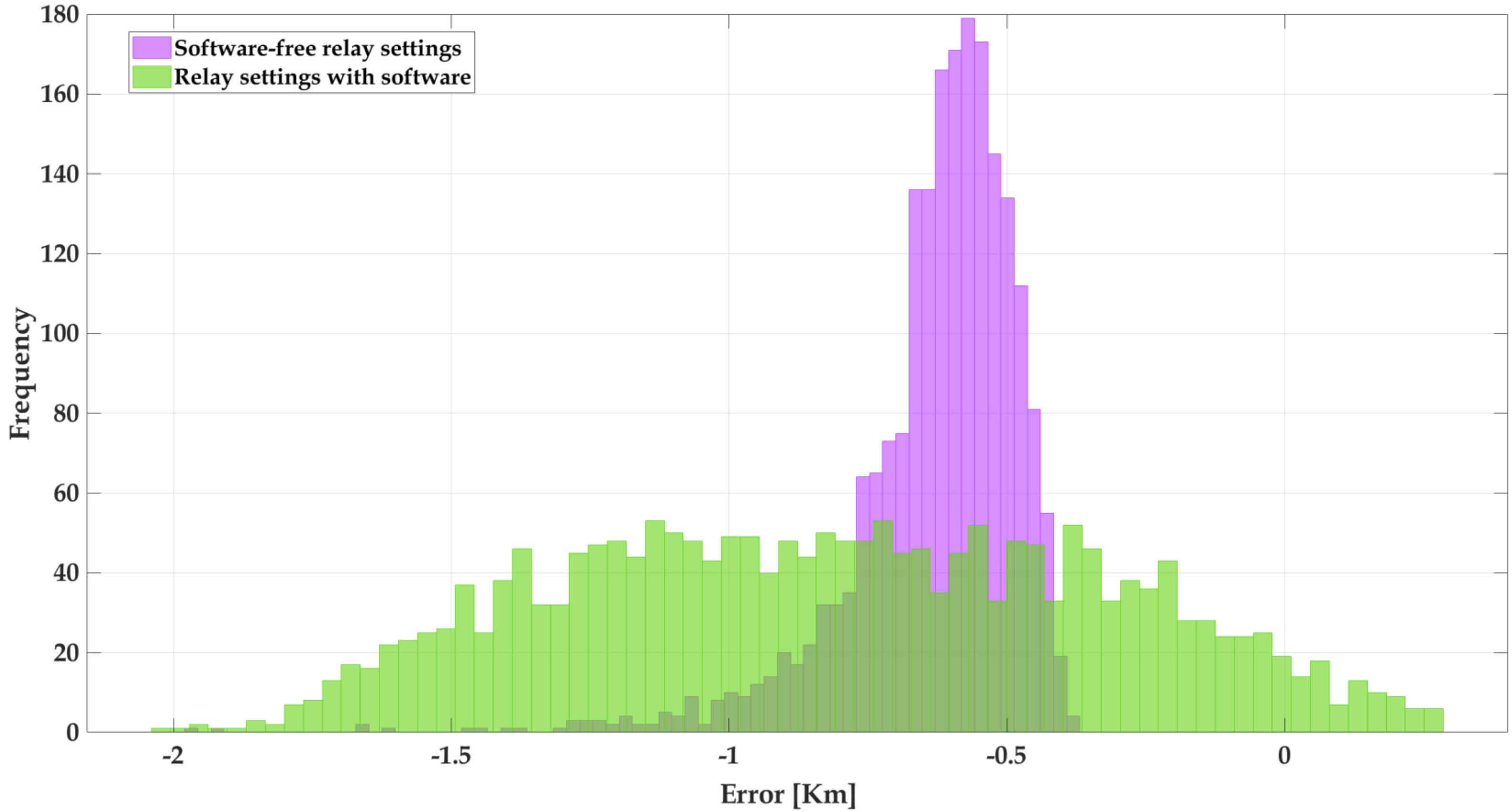
1) u_{13} = radius of the conductor of submarine section
2) u_{17} = thickness of the lead sheath of submarine section
3) u_{15} = thickness of the insulation layer of submarine section

- The relay settings ($Z_{0,}$ Z_1) are computed with commercial software tools…



Step 9a. Estimate the output uncertainty

- Compare the output distribution in the two scenarios



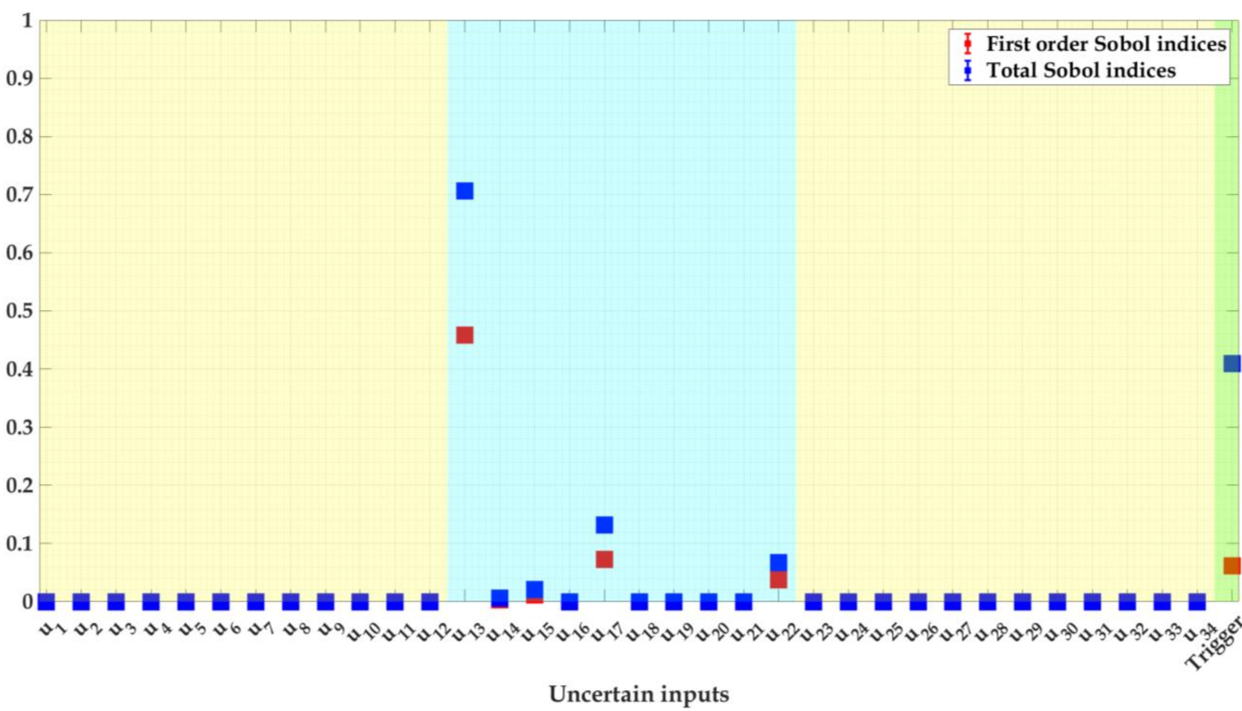
- The commercial software tool does have an impact! Let us confirm this with SA…

PART 2 – Application of Sensitivity Analysis
Step 9b. Extract the sensitivity indices - TRIGGER

- Error = f (**u**)
- **u** = [u_1, …, u_{34} , **Trigger**]
  - Cable geometrical data
  - Cable cross-section data
  - Earth resistivity
  - Trigger

	u_1	u_2	u_3	…		u_{34}	Trigger
1	16.3654	1.4960	16.6099	1.4313	3.3439	559.1927	1
2	17.2914	1.5311	15.6310	1.5648	3.5953	445.0905	0
3	16.9267	1.5708	16.3316	1.5010	3.4698	126.4021	1
4	17.8460	1.4560	15.3027	1.4847	3.5459	969.7573	0
5	16.2893	1.5037	15.4236	1.5225	3.6697	676.8663	0
6	17.2086	1.4686	16.0416	1.4639	3.3964	296.6422	1
7	16.5783	1.4294	15.9461	1.4514	3.5330	251.6648	0

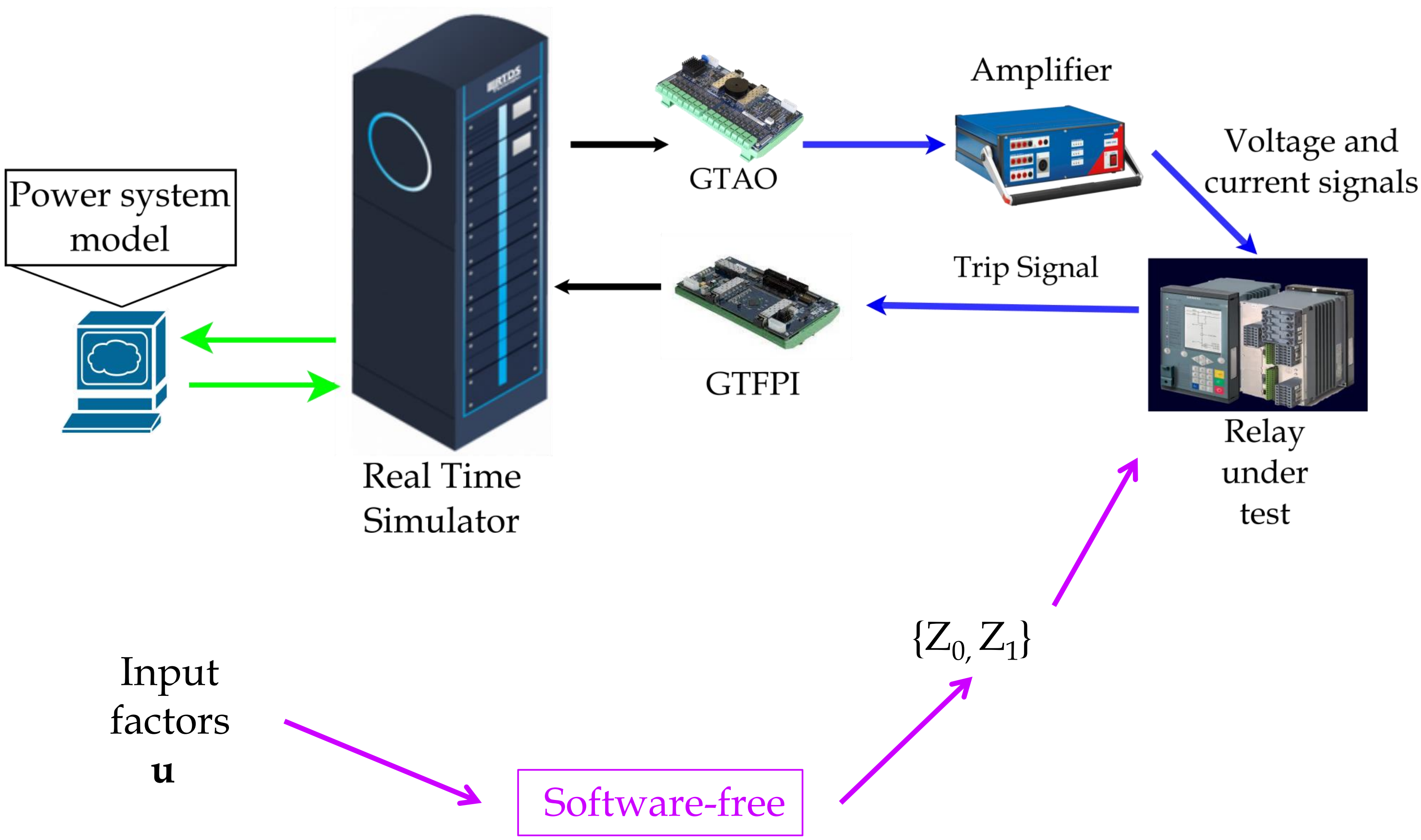
If **Trigger** = 0 then relay settings with software
If **Trigger** = 1 then software-free relay settings



3. Do certain modeling choices affect the relay performance?

YES!
Let us proceed with the software-free scenario.

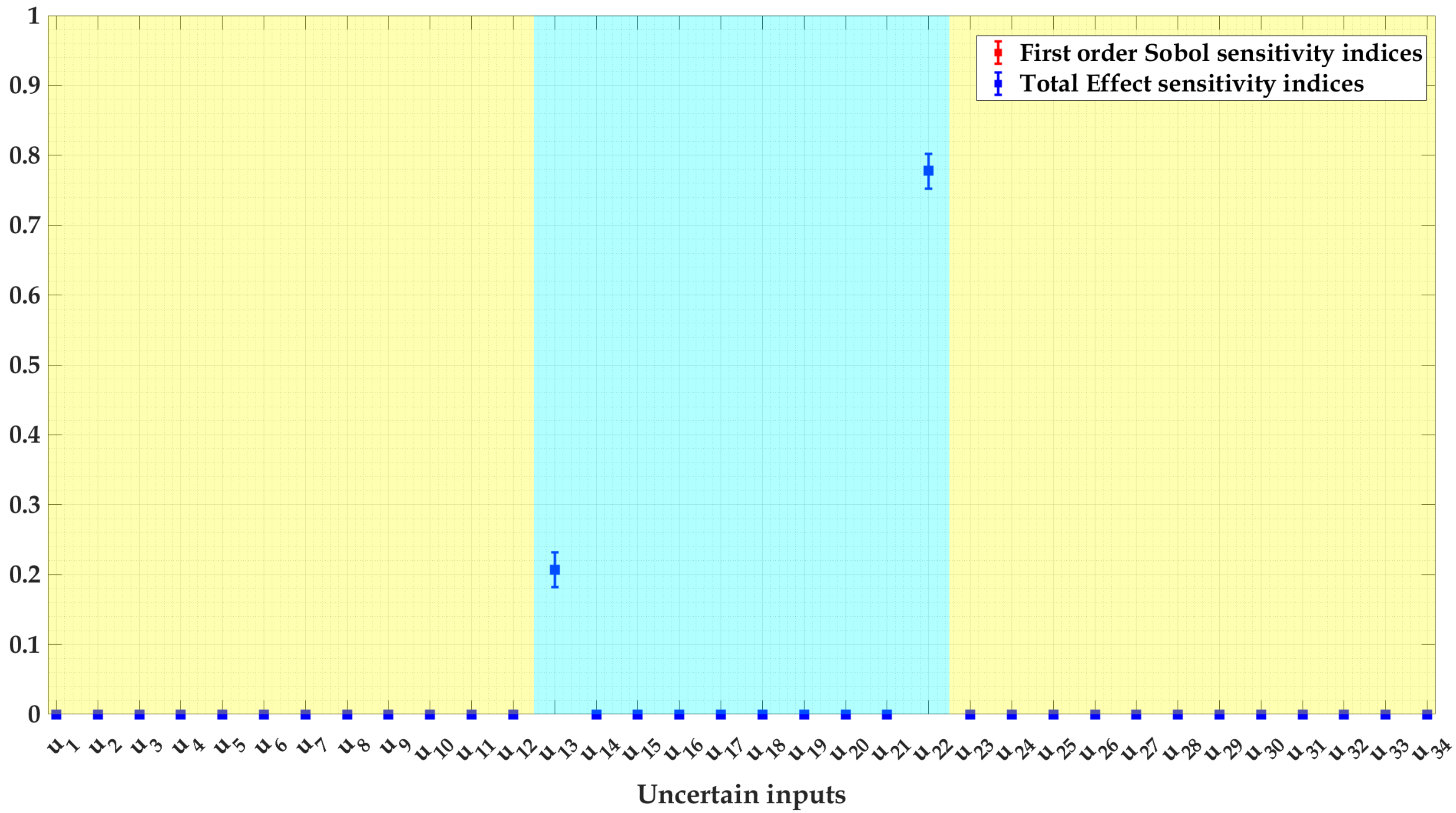
Step 9b. Extract the sensitivity indices



Step 9b. Extract the sensitivity indices

1) u_{22} = earth resistivity ("sand with sea-water") of submarine section
2) u_{13} = radius of the conductor of submarine section

Sample size N = 128



PART 2 – Application of Sensitivity Analysis
Step 4. Identify the inputs

- Error = f (**u**)
- **u** = [u_1, …, u_{35}]
  - Cable geometrical data
  - Cable cross-section data
  - Earth resistivity
  - Fault location

	Name	Description	Units	Nominal value	Range
Land cable (UG_1–UG_2)	u_1, u_{23}	Radius of the conductor	mm	17	[16.15, 17.85]
	u_2, u_{24}	Thickness of the conductor screen layer	mm	1.5	[1.425, 1.575]
	u_3, u_{25}	Thickness of the cross-linked polyethylene (XLPE) insulation layer	mm	16	[15.2, 16.8]
	u_4, u_{26}	Thickness of the XLPE insulation screen layer	mm	1.5	[1.425, 1.575]
	u_5, u_{27}	Thickness of the lead sheath	mm	3.5	[3.325, 3.675]
	u_6, u_{28}	Earth resistivity (dry inland soil)	Ωm	–	[20, 1000]
	u_7, u_{29}	x_1 coordinate of the cable	m	-0.5	[-0.475,-0.525]
	u_8, u_{30}	x_2 coordinate of the cable	m	0	[-0.05, 0.05]
	u_9, u_{31}	x_3 coordinate of the cable	m	0.5	[0.475, 0.525]
	u_{10}, u_{32}	y_1 coordinate of the cable	m	0.75	[0.5, 1]
	u_{11}, u_{33}	y_2 coordinate of the cable	m	0.75	[0.5, 1]
	u_{12}, u_{34}	y_3 coordinate of the cable	m	0.75	[0.5, 1]
Submarine cable	u_{13}	Radius of the conductor	mm	13.25	[12.59, 13.91]
	u_{14}	Thickness of the conductor screen layer	mm	2	[1.9, 2.1]
	u_{15}	Thickness of the insulation layer	mm	15	[14.25, 15.75]
	u_{16}	Thickness of the XLPE insulation screen layer	mm	1.5	[1.425, 1.575]
	u_{17}	Thickness of the lead sheath	mm	2.1	[1.995, 2.205]
	u_{18}	Thickness of the semiconducting PE	mm	2	[1.9, 2.1]
	u_{19}	Thickness of the armour bedding	mm	1.5	[1.425, 1.575]
	u_{20}	Thickness of the armour	mm	6	[5.7, 6.3]
	u_{21}	Thickness of the outer serving	mm	4.5	[4.275, 4.725]
	u_{22}	Earth resistivity (sand with seawater)	Ωm	–	[0, 500]
	u_{35}	Fault location along the transmission line	km	–	[0, 54]

PART 2 – Application of Sensitivity Analysis

Step 9. Estimate the output uncertainty / Extract the sensitivity indices

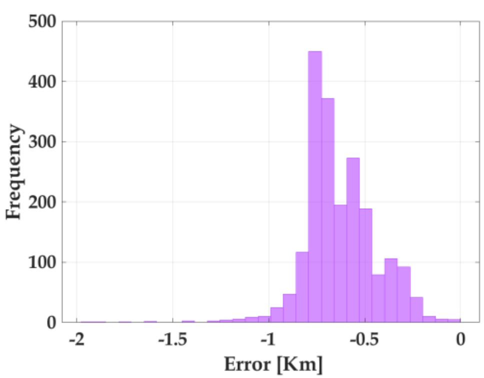
- Error = f (**u**)
- **u** = [u_1, …, u_{35}]
  - Cable geometrical data
  - Cable cross-section data
  - Earth resistivity
  - Fault location

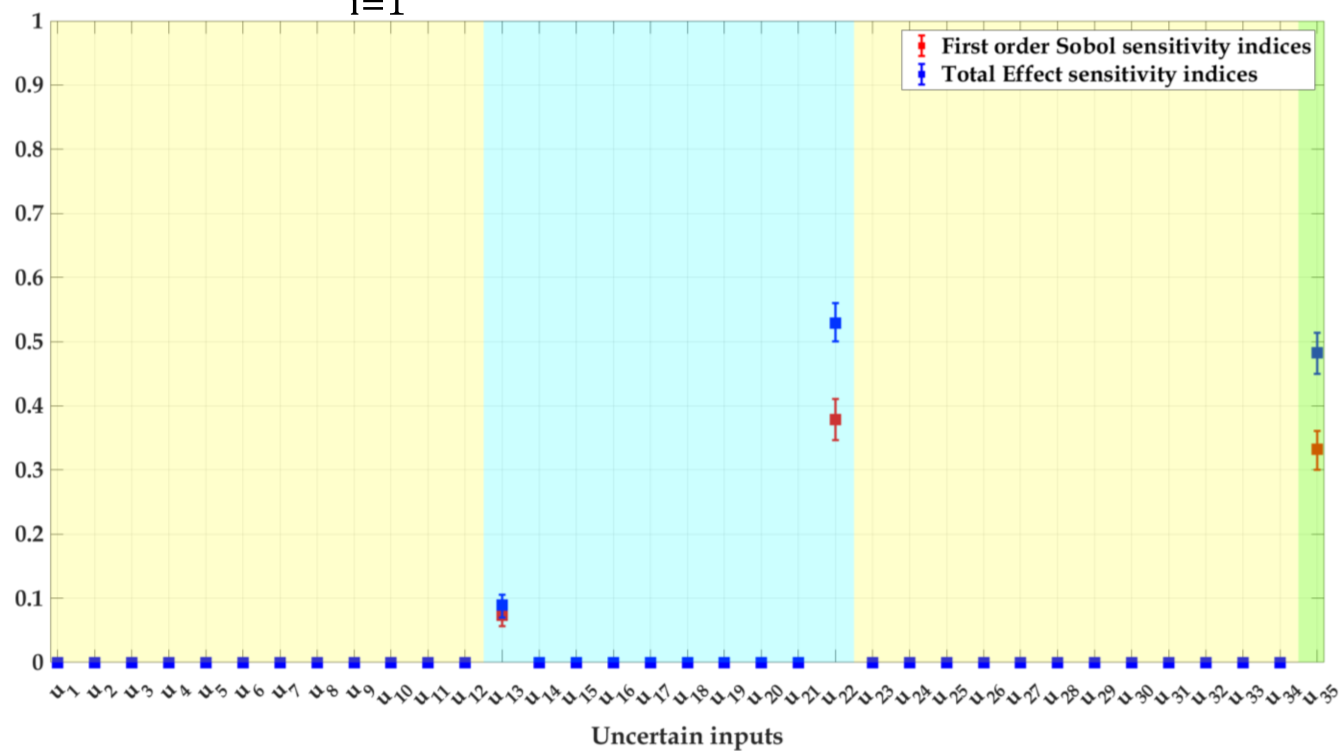
1) u_{22} = SM earth resistivity
2) u_{35} = fault location
3) u_{13} = SM radius of the conductor

$$1 - \sum_{i=1}^{K} S_{u_i} = 0.18$$

$$S_{\{u_{22},u_{35}\}} = 0.15$$

$$S_{\{u_{13},u_{35}\}} = 0.03$$





Step 10. Interpret the results

- Error = f (**u**)
- **u** = [u_1, …, u_{35}]
  - Cable geometrical data
  - Cable cross-section data
  - Earth resistivity
  - Fault location

1) u_{22} = earth resistivity of submarine section
2) u_{35} = fault location
3) u_{13} = radius of the conductor of submarine section

$$1 - \sum_{i=1}^{K} S_{u_i} = 0.18$$

$$S_{\{u_{22},u_{35}\}} = 0.15$$
$$S_{\{u_{13},u_{35}\}} = 0.03$$

- Which recommendations?
  - Earth resistivity (controllable) > fault location (uncontrollable): work on the better characterization of the earth resistivity
    - Measure the earth resistivity (step-wise definition)
    - Measure Z_0 and Z_1 from field test or retrieve them from fault records
  - Increase (if technically feasible/economically convenient) the quality control of the conductor radius (inolve the production process of the cable manufacturers)

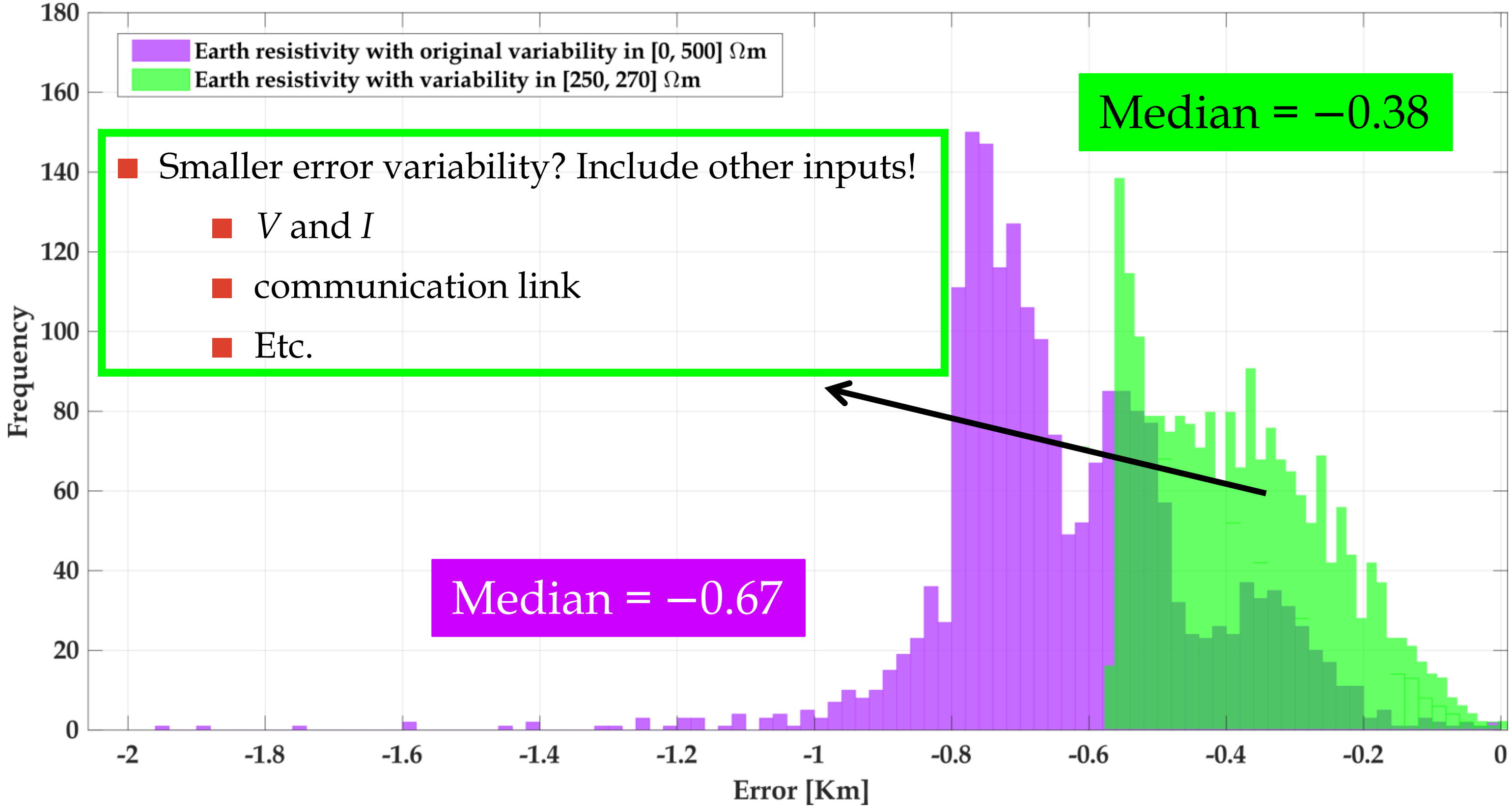
1. Which of the uncertainty sources contribute to the relay performance the most?

- The tolerance of all the other cable parameters is totally OK!

2. Do any of the uncertainty sources have a negligible impact on the relay performance?

Application of Sensitivity Analysis
On the "factor prioritization" setting

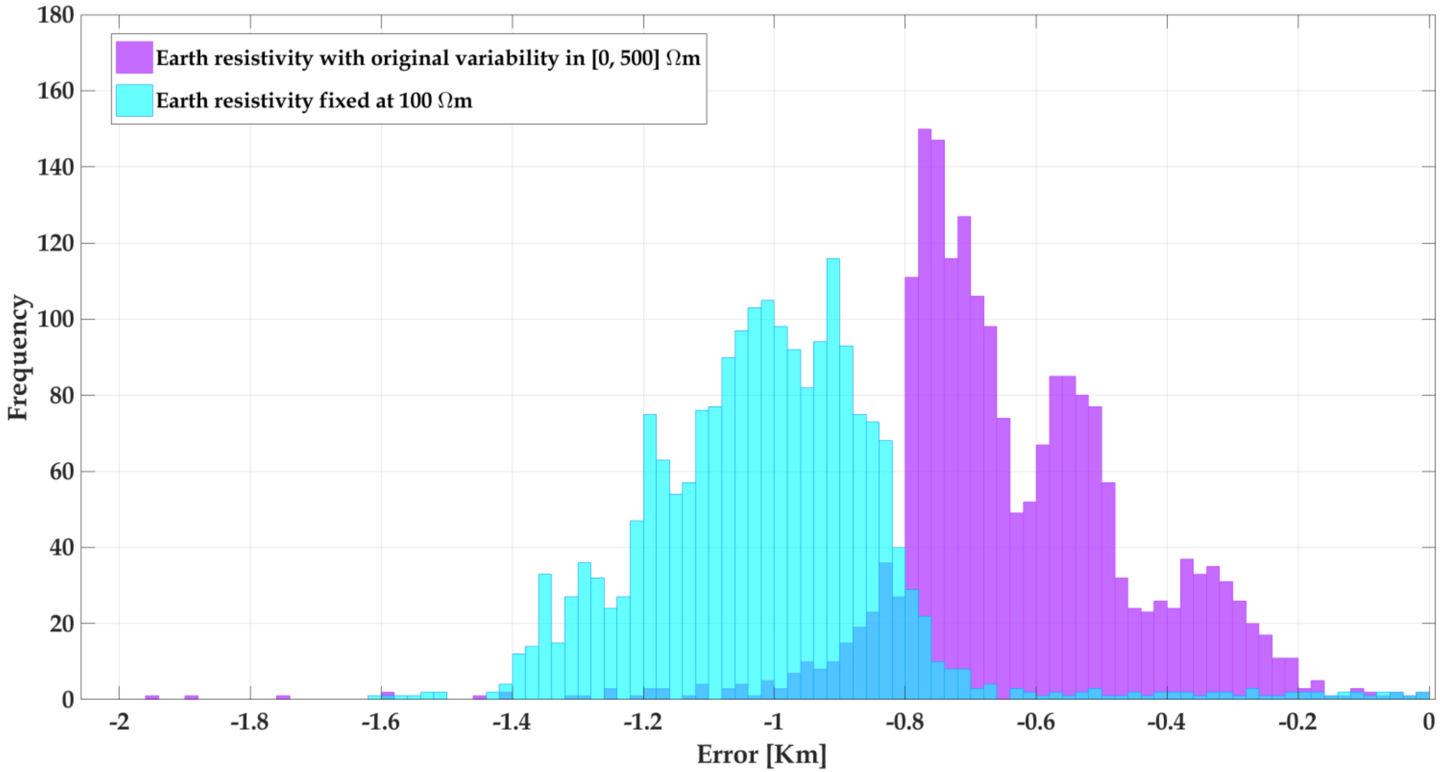
- Based on **<u>first order</u>** Sobol' indices
- Submarine earth resistivity is ranked first → reduce its variability (e.g., field tests)
- Let us *simulate* the earth resistivity measurement
  - Variability around the "optimal" value in [250, 270] Ωm



- Smaller error variability? Include other inputs!
  - *V* and *I*
  - communication link
  - Etc.

Application of Sensitivity Analysis
On the "factor prioritization" setting

- Based on **first order** Sobol' indices
- Submarine earth resistivity is ranked first → reduce its variability (e.g., field tests)
- Let us *simulate* the earth resistivity measurement
  - Fixed at the ''default'' value of 100 Ωm



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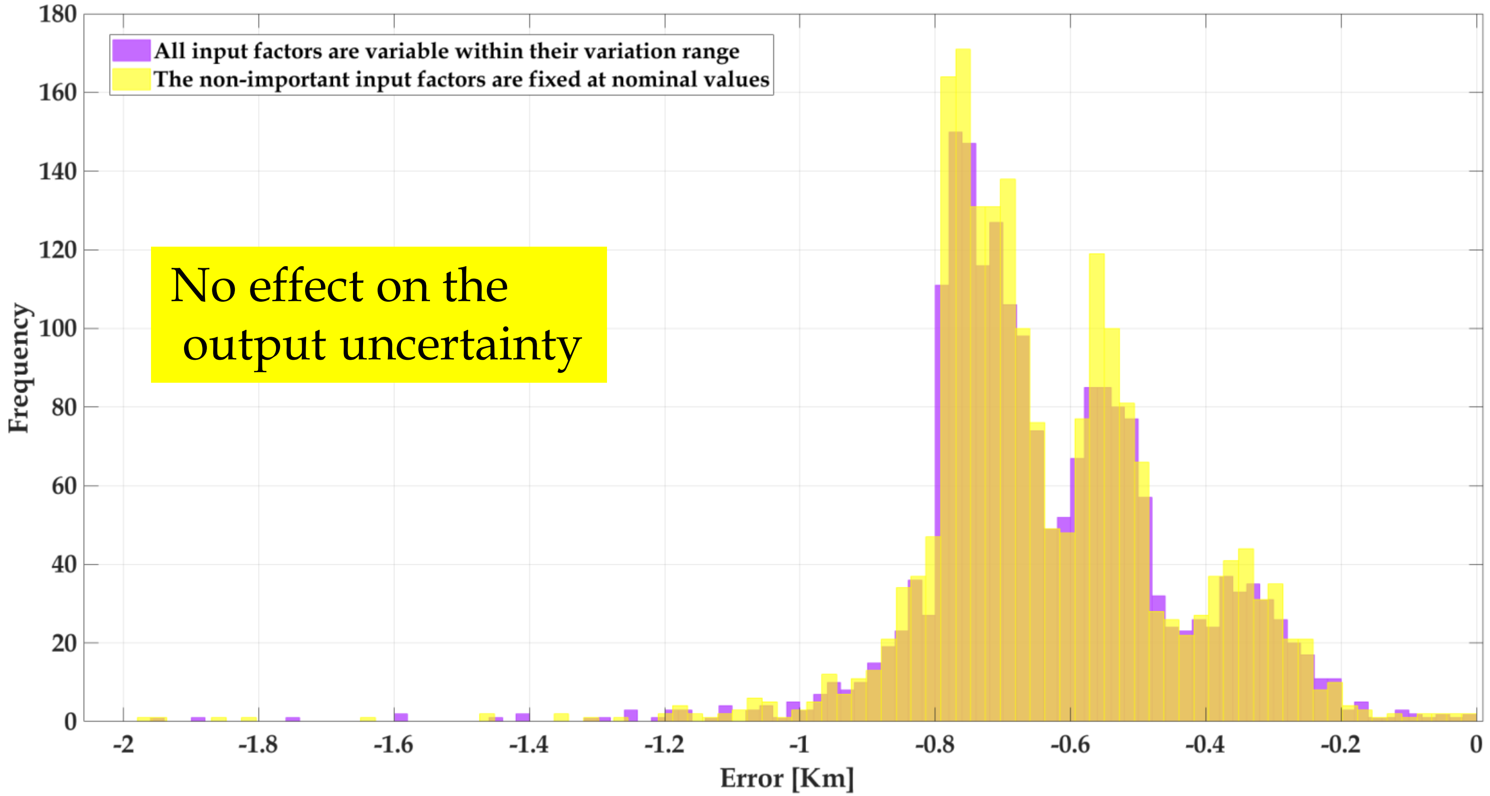
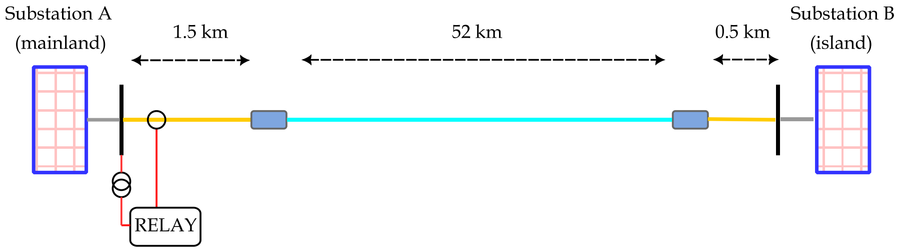
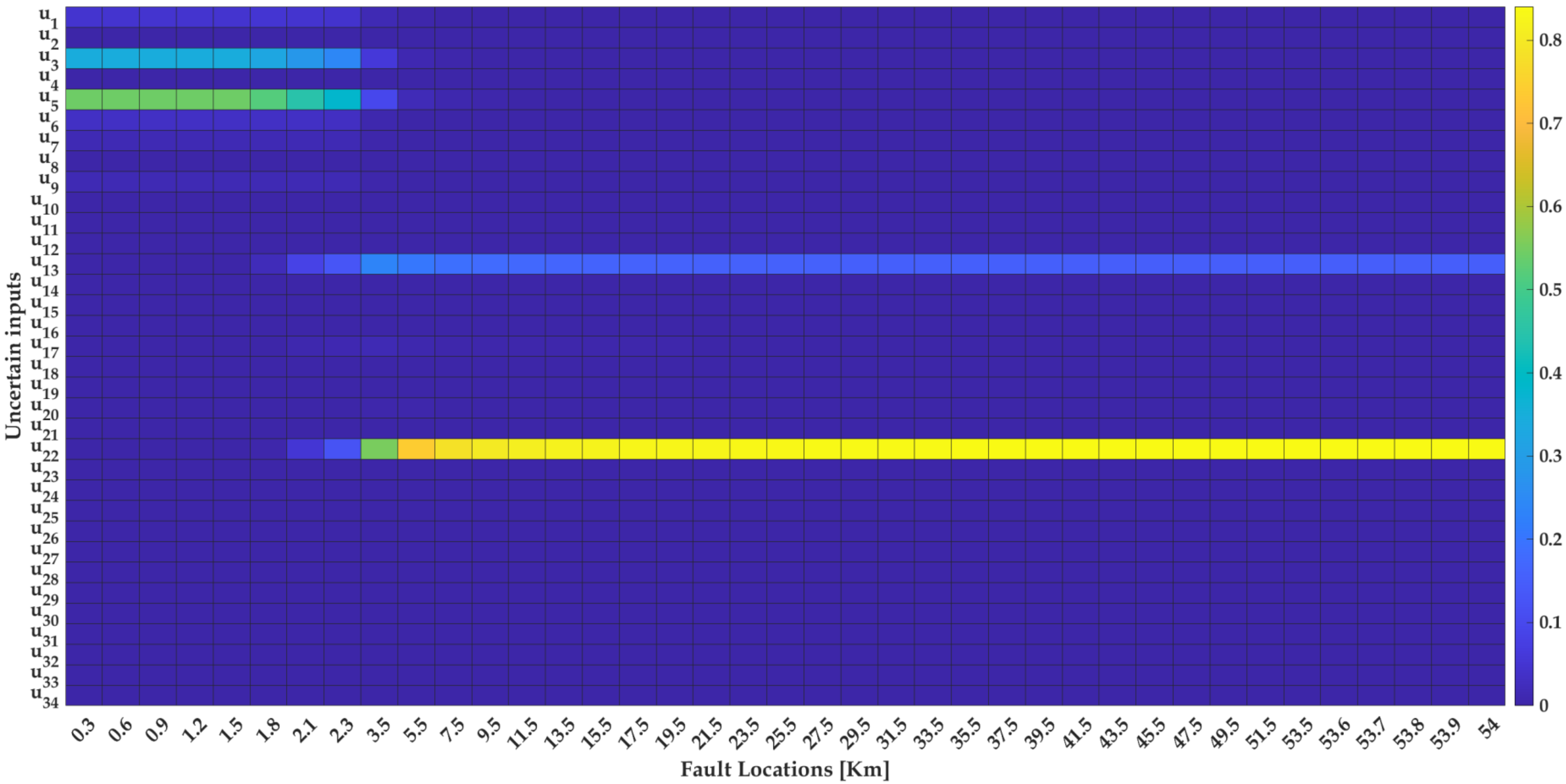
Application of Sensitivity Analysis
On the "factor fixing" setting

- Based on **<u>total effect</u>** indices
- All input factors except three have null indices → fix them at any value within their PDF



- Heatmap to visualize 3D information





PART 1: Introduction and description of the case study
PART 2: Application of Sensitivity Analysis
PART 3: Sensitivity Analysis for multi-scale models

Recasting our problem into the micro- and macro- model structure

- Let us recall…
- Micromodels:
  - $z_1 = g(\mathbf{x})$, with $\mathbf{x} \in \mathbb{R}^n$ $\longrightarrow$ $Z_0 = g(\mathbf{u})$, with $\mathbf{u} \in \mathbb{R}^{34}$
  - $z_2 = h(\mathbf{y})$, with $\mathbf{y} \in \mathbb{R}^m$ $\longrightarrow$ $Z_1 = h(\mathbf{u})$, with $\mathbf{u} \in \mathbb{R}^{34}$
- Macromodel:
  - $w = f(z_1, z_2)$
  - $w = f(g(\mathbf{x}), h(\mathbf{y})) = f(\mathbf{x}, \mathbf{y})$ $\longrightarrow$ $\text{Error} = f(Z_0, Z_1) = g(\mathbf{u}) + h(\mathbf{u})$

- If we recast our problem into this form…
  - $Z_0 = g(\mathbf{u})$, with $\mathbf{u} \in \mathbb{R}^{34}$
  - $Z_1 = h(\mathbf{u})$, with $\mathbf{u} \in \mathbb{R}^{34}$

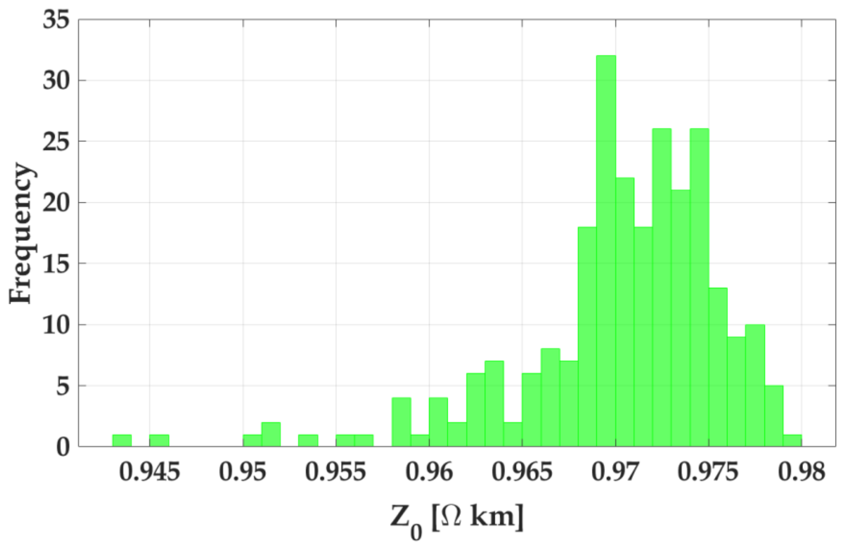
    $\mathbf{u} = [u_1, \dots, u_{34}]$ is composed of:
    - Cable geometrical data
    - Cable cross-section data
    - Earth resistivity
  - $\text{Error} = f(Z_0, Z_1) = g(\mathbf{u}) + h(\mathbf{u})$

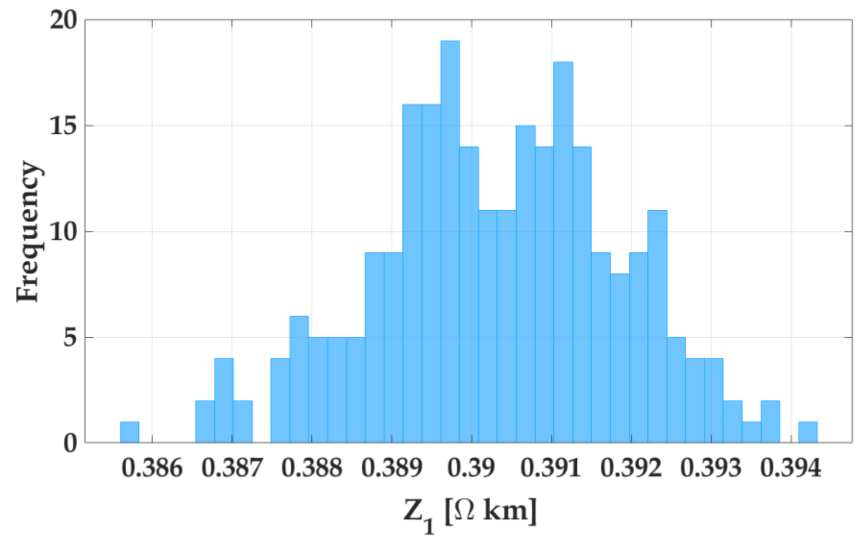
- If $\mathbf{x} = \mathbf{y}$, and $f(\mathbf{x}) = g(\mathbf{x}) + h(\mathbf{x})$…
- …then $T_{\mathbf{u}_i}$ of $f(\mathbf{x}) \leq 2 \max \{T_{\mathbf{u}_i}$ of $g(\mathbf{x})$, $T_{\mathbf{u}_i}$ of $h(\mathbf{x})\}$

- We are interested in the GSA of Error with respect to $\mathbf{u}$ (for factor screening).
- We assume that GSA of Z_0, Z_1 is cheaper than GSA of Error.
  - $T_{\mathbf{u}_i}$ of Error $\leq 2 \max \{T_{\mathbf{u}_i}$ of Z_0, $T_{\mathbf{u}_i}$ of $Z_1)\}$ $\longrightarrow$ Let us verify it!

Step 9a. Estimate the output uncertainty

- Micromodels:
  - $Z_0 = g(\mathbf{u})$
  - $Z_1 = h(\mathbf{u})$
- $\mathbf{u} = [u_1, \ldots, u_{34}]$
  - Cable geometrical data
  - Cable cross-section data
  - Earth resistivity

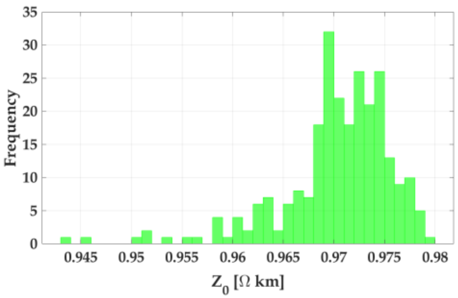


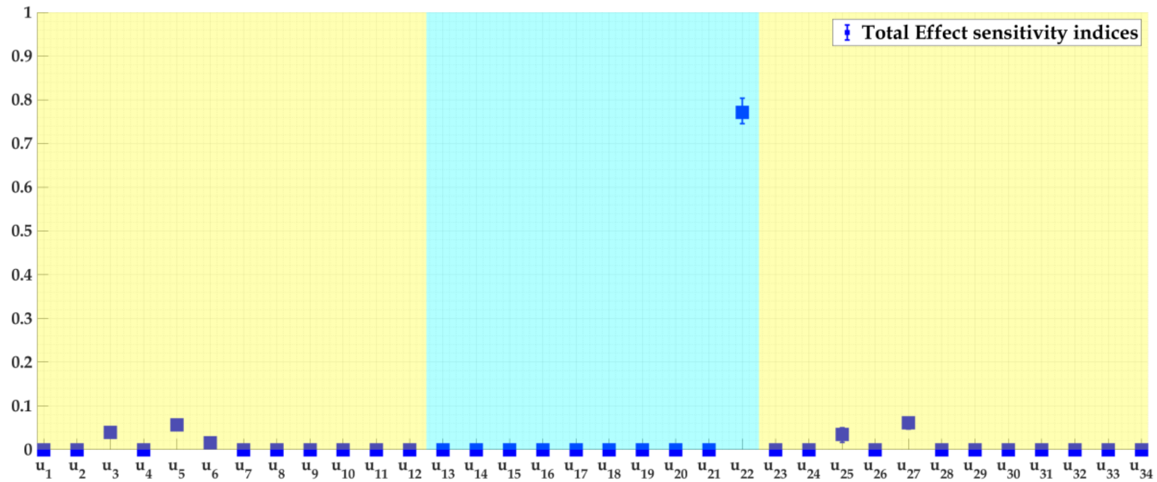


PART 3 – Sensitivity Analysis for multi-scale models

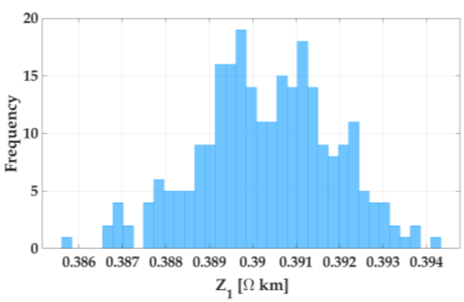
Step 9b. Extract the sensitivity indices

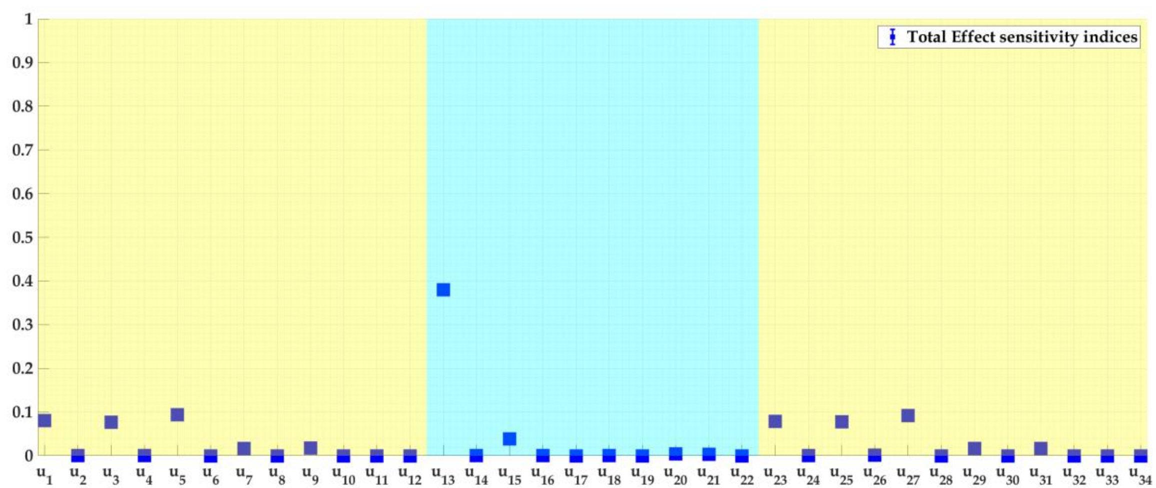
Z_0





Z_1

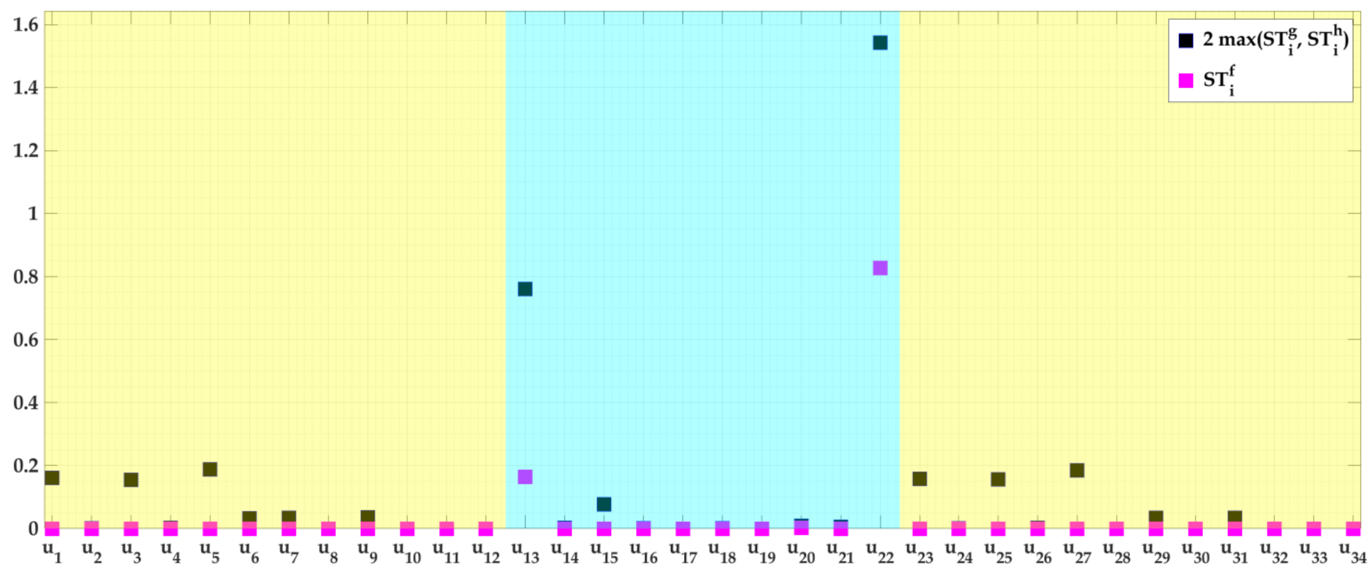




Step 9a. Estimate the output uncertainty

- Macromodel:
  - Error = $f(Z_0, Z_1) = g(\mathbf{u}) + h(\mathbf{u})$
- $\mathbf{u} = [u_1, \ldots, u_{34}]$
  - Cable geometrical data
  - Cable cross-section data
  - Earth resistivity

Error



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