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Empirical findings on European Critical Infrastructure Dependencies

H.A.M. Luiijf*

A.H. Nieuwenhuijs

M.H.A. Klaver

TNO Defence, Security and Safety, P.O. Box 96864, 2509 JG The Hague, The Netherlands
E-mail: {eric.luiijf, albert.nieuwenhuijs, marieke.klaver}@tno.nl

M.J.G. van Eeten

E. Cruz

Faculty of Technology, Policy and Management, Delft University of Technology, Delft, The Netherlands
E-mail: m.j.g.vaneeten@tudelft.nl, editecruz@gmail.com

* Corresponding author

Abstract: One type of threat consistently identified as a key challenge for Critical Infrastructure Protection (CIP) is that of dependencies and interdependencies among different critical infrastructures (CI). This article draws on a hitherto untapped data source on infrastructure dependencies: a daily maintained database containing over 4500 serious disruption events in different CI all over the world as reported by news media. This article analyzes this empirical data set to discover patterns in CI failures in Europe like cascading, dependencies, and interdependencies. Some analysis results area that less sectors than many dependency models suggest drive cascading outages and that interdependencies are hardly reported.

Keywords: Critical infrastructure, dependency, interdependency, cascading, data, Europe.

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Biographical notes: *Eric Luiijf M.Sc(Eng)Delft* obtained his Masters degree in Mathematics at the Technical University Delft in 1975. After his duties as officer in the Royal Netherlands Navy, he joined the Netherlands Organisation for Applied Scientific Research TNO. Eric is currently employed by TNO Defence, Security

and Safety as Principal Consultant Information Operations and Critical Infrastructure Protection. His research comprises defensive information operations/ information assurance and the protection of Critical (Information) Infrastructures, both nationally and at the European level in projects like ACIP, VITA, CI^{2}RCO, EURAM, IRRIIS, DIESIS and EURACOM.

Albert Nieuwenhuijs M.Sc. obtained his Masters degree in Mechanical Engineering at the Technical University Twente in 1990. He started his career as technical and organization consultant and project manager with several companies before joining TNO Defence, Security and Safety in 2001. As scientist he works on the topics critical infrastructure protection (CIP) and risk analysis. He is involved in various Dutch CIP projects as well as in European projects like VITA, EURAM, and IRRIIS.

Marieke Klaver PhD studied Mathematics at the University of Leiden. After her PhD in 1990, she joined TNO. Since 1997, Marieke takes part in TNO's R&D efforts in information operations and information assurance, and Critical (Information) Infrastructure Protection. She is involved in Dutch CIP studies like the one in support of the Dutch Strategic Council for Critical Infrastructures (SOVI), and in EU CIP projects. As programme manager, she is responsible for a TNO R&D programme on Security and Infrastructures commissioned by the Ministry of Interior and Kingdom Relations.

Michel van Eeten is Professor of Public Administration at the Faculty of Technology, Policy and Management, Delft University of Technology, the Netherlands. He also teaches in several programs for executive education at the Netherlands School of Public Administration in The Hague. His research has focused on the governance of infrastructures, most notably on the issue of internet security. He has also done published on the reliability of electricity, telecommunication and transportation networks. Recent work as a policy analyst includes consulting for the Dutch Ministry of Economic Affairs, the United Nations International Telecommunications Union and the OECD.

Edite Cruz performed the initial data analysis on the outage database contents while doing her MSc student thesis at the School of Technology, Policy and Management at Delft University of Technology.

1. Introduction

Many nations in Europe and abroad as well as the European Union have identified that critical infrastructure (CI) dependencies and interdependencies are of major concern to them. Failure within a single CI may be damaging to society, but if such failure cascades then the potential for multi-infrastructural collapse and high catastrophic damages might be high. Various modeling and simulation efforts in the USA and Europe try to simulate CI cascading effects in order to understand the dependency risk to its full extend. But just how to rate this type of risk in comparison to other CI risk factors remains unclear. While probabilities are unknown, the magnitude of the consequences – a multi-sector collapse – is so large that many argue that this factor alone pushes the CI dependency risk to the top of national priority lists. Auerswald calls CI dependencies the "unmanaged challenge," which have proven to be less tractable than managing the vulnerabilities within a single infrastructure: "More pervasive and difficult to manage are the (inter)dependencies that exist among firms in different infrastructures" (Auerswald, 2006). Many of the CIP policies also identify such dependencies as a priority. Adequately addressing this “unmanaged challenge” will draw substantial resources away from other areas within CIP. The question is whether the risk associated with CI dependencies, and if so, for which set of CI, needs to be prioritized. A confrontation with empirical data, even if scarce or incomplete, may help in decision-taking and prioritizing. So far, such efforts – as far as the authors know – are by and large missing.

This paper draws on a hitherto untapped data source on infrastructure dependencies: a database containing over 4500 reports by June 2009 on serious CI failures and their cascading outages as reported by news media all over the world (TNO, 2009). The authors regularly analyze this data set in order to discover patterns in CI failures across different CI in the world, in Europe and nationally. This paper concentrates on the analysis of the data collected about CI failures in European nations.

1.1 Outline

Before turning to our analysis, subsection 1.2 presents the definitions of some terms which we use in this article. Section 2 reviews the state-of-the-art in CI dependency and interdependency research and presents a discussion about empirical data collections about CI. Section 3 discusses the scope, method and limitations of our analysis. Section 4 discusses our analysis of CI disruptions and cascading events for Europe at large. In Section 5 we discuss the implications of our analysis for the national and international CIP efforts regarding dependencies and interdependencies.

1.2 Definitions

A *cascade initiating event* is an event that causes a subsequent event in another CI.

A *cascade resulting event* is an event that results from an event in another CI.

According to (EC, 2008) a *critical infrastructure (CI)* means an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions.

A *CI dependency* is the relationship between two CI products or services in which one product or service is required for the generation of the other CI product or service (Rinaldi, Peerenboom, and Kelly, 2001).

An *independent event* is an event that is neither cascade initiating nor cascade resulting.

A CI interdependency is defined as the mutual dependency of CI products or services (Nieuwenhuijs, Luiijf, and Klaver, 2008).

2 Current state of the art in CI dependency research

2.1 CI dependencies

Earlier theoretical CI dependency works describe CI dependency models based upon taxonomies or frameworks, e.g., (Rinaldi, Peerenboom, and Kelly, 2001), and (Svendsen and Wolthuysen, 2006). A small set of sources on CI disruptions stems from post-mortem analyses of larger disruption events within a single CI sector, e.g. about big blackouts such as the blackout in a large number of European nations and Morocco (UCTE, 2006). Another set of sources on CI disruptions and their cascading effects stem from government post mortem assessment reports on their emergency response actions and failures after major emergencies, e.g., (Von Kirchbach, 2003). Moreover, CI dependency modeling and simulation efforts increasingly take place in various nations, see e.g., (Pederson et al, 2006). In general, however, such CI models are based on a collections of simplified theoretical dependencies between CI and not on real-life data or on a full dependency analysis of past CI disruption events.

The empirical work in this article discusses CI dependencies based on analysis of a large set of news reports about serious CI disruptions which are recorded in a unique CI disruptions and outages database (TNO, 2009). Partially based on the insights gained during the collection of the data records and on the analytical findings described in this article, the theoretical understanding and modeling of CI dependencies and interdependencies has advanced considerably as has been reported in (Nieuwenhuijs, Luiijf, and Klaver, 2008).

2.2 Empirical data on CI disruptions

Globally, there are a number of databases which focus on collecting empirical data of CI incidents. Without exception, however, these databases focus on a specific environment, a single CI sector, or on a specific threat. Examples of foci of such databases are for instance terrorism-caused energy infrastructure disruptions, safety incidents in the process industry, electric power disturbances (e.g., by national regulators), IAEA nuclear incidents, and risk databases by reinsurance companies.

Examples of such recordings are, for instance, the US North American Energy Reliability Council (NERC) power disturbance database and the US Office of Pipeline Safety (OPS) incident database. Simonoff et al, 2008, used these databases for their USA energy disruption analysis and the related environmental impact and financial loss.

The authors found only one database (Zimmerman and Restrepo, 2008) which includes a limited number of CI disruptions at a local level and their cascading effects. The database was constructed for developing analytical analysis approaches. It did not intend to be complete and to collect a large set of CI disturbance data. Actually, the authors did not identify global databases which focus on *serious* disturbances of all CI and their cascading effects on other CI in an all-hazards approach with the exception of the one described below.

3 CI dependency analysis based on empirical data

At the core of this CI dependency analysis is a daily maintained database by TNO with public reports on serious CI disruptions and their cascading effects. The data is collected from public sources like newspapers and internet news outlets in eight languages, if possible augmented by official incident reports. A report on an incident in one of the CI sectors would be added to the database based on the event impact, e.g., only CI disruptions affecting 10.000 customers (power) or passengers (transport) or events which had a prolonged effect or recovery time for many citizens. Each database record contains the affected sector, the affected service, the initiating event (if any), the CI operators' name, start time and date, end time and date, country, geographic area within country, raw size of affected area, a textual description of cause, the threat category and –subcategory, an indication of the disruption consequences and impact, the recovery duration, and one or more (web) references are recorded.

While data is collected globally, this analysis focuses on a subset: the CI disruption events in Europe. These comprise 2103 CI service failure events which occurred in 32 European nations. Another 2425 CI services failure events stem from 89 non-European countries and cyberspace. Based on this data, we are able to empirically study CI dependencies and interdependencies both per nation, multi-national region, and globally. Data analysis provides a sense of the degree in which failure in one CI cascades into a *serious* failure in others – i.e., what part of overall disruptions can be attributed to CI dependencies and interdependencies. This analysis is performed at the level of CI services. This means that we only consider a *resulting event* to be a dependency -and include it into the results- if the resulting event takes place in another CI service than the initiating CI event.

For readability, the results below are often aggregated to the CI sector level. Consequently, dependencies within a single CI sector appear. These are dependencies between the underlying CI services within the CI sector at hand (e.g., gas provided to power generation). Only in some cases results at each CI service level are presented.

We have explored the validity of our findings by triangulating different data sources. This triangulation effort can only marginally compensate for the significant limitations of using public news reports as the main source of data. There are many biases, for instance the reporting practices of news media. Not every incident above the threshold we use will be reported in the news. News reports likely reflect what the news outlets assume is of interest to their public audiences. At the same time, some detailed information about the event has to be available in an easy way. A power disruption hardly goes unnoticed, while information about a financial sector wholesale failure may not reach the press. Other biases may be the limited set of languages that we track for CI disruptions (Dutch, English, French, German, Italian, Portuguese, Spanish, and Swedish). It is not clear if and how our findings are affected by these limitations. We are not aware of any research that has studied biases in how the media report on CI failures. That said, the authors believe that in light of the overall paucity of empirical research on this topic our analysis contributes much needed data to the policy debates on CIP and the risk of CI cascading failure.

4. Dependencies across Critical Infrastructures in Europe

In the various dependency analyses below, we classify the events in *cascade initiating events*, *cascade resulting events* and *independent events* (as defined in subsection 1.2). These categories are not mutually exclusive as events can be both cascade initiating and cascade resulting events. This causes the sum of cascade initiating, resulting and independent events to exceed the total number of recorded events (see 'total' columns in **Table 1** and **Table 2**).

4.1 Number of cascades

We have first analyzed the data by distinguishing cascading events from non-cascading events (**Table 1**). Interestingly, 29% of the reported incidents result from incidents in other CI services (**Table 2**, cascade resulting). The anecdotal evidence about CI dependencies and cascading sometimes conveys the sense of rather unlikely scenarios, suggesting that cascades are events of low probability and high consequence. Our data, however, shows that they occur frequently and make up a significant portion of the *serious* CI outages in Europe.

Table 1. Categorization of number of CI disruption events (absolute number of events).

CI Sector	Cascade initiating	Cascade resulting	Independent	Total	Sample size
Education	0	3	1	4	4
Energy	174	93	462	729	708
Financial services	3	33	58	94	94
Food	1	8	5	14	14
Government	2	43	28	73	72
Health	1	17	26	44	44
Industry	7	15	7	29	29
Internet	22	79	105	206	204
Postal	1	0	0	1	1
Telecommunications	87	155	140	382	368
Transport	20	150	299	469	468
Water	10	25	64	99	97
Total	328	521	1195	2144	2103

Table 2. Percentage categorization of number of CI events per CI sector.

CI Sector	Cascade initiating	Cascade resulting	Independent	Total	Sample size
Education	0%	75%	25%	100%	4
Energy	25%	13%	65%	103%	708
Financial services	3%	35%	62%	100%	94
Food	7%	57%	36%	100%	14
Government	3%	60%	39%	102%	72
Health	2%	39%	56%	100%	44
Industry	24%	52%	24%	100%	29
Internet	11%	39%	51%	101%	204
Postal	100%	0%	0%	100%	1
Telecommunications	24%	42%	38%	104%	368
Transport	4%	32%	64%	100%	468
Water	10%	26%	66%	102%	97
Total	15,6%	29,5%	56,8%	101,9%	2103

4.2 Directionality of cascades

Another view is in which CI sector does an event originate and which CI sectors are affected (**Table 3**). The not cascade-related events are labeled 'no sector'. These are external disruption events such as storm/hurricane, avalanche, ice, deliberate human attacks, economic factors and internal failures (e.g., human error, technical failure). From **Table 3** one can derive that the energy and telecommunication sectors are the main cascade initiating sectors. The energy sector is the only sector which initiates more cascades than it ends up receiving. Note that we grayed-out those figures that are of a low statistical relevance in all the tables presented in this article.

Table 3. Events categorized by initiating sector and affected sector (# of events).

		Initiating sector											
		No sector	Energy	Financial Services	Food \ Postal	Government	Health	Industry	Internet	Telecom	Transport	Water	**Grand Total**
Affected sector	Education	1	1									2	4
	Energy	615	83					4		2	1	3	708
	Financial services	61	6	6					3	18			94
	Food	6	3		1			3			1		14
	Government	29	18			1	1	1	4	16	1	1	72
	Health	27	11				2			3		1	44
	Industry	14	12					1			1	1	29
	Internet	125	19						18	42			204
	Postal services	1											1
	Telecom	213	76					1	1	71	6		368
	Transport	318	118		1	1		3		7	15	5	468
	Water	72	17					5				3	97
	Total	**1482**	**364**	**6**	**2**	**2**	**3**	**18**	**26**	**159**	**25**	**16**	**2103**

When disregarding the not cascade-initiated events ('no sector'), the data analysis confirms that the CI dependency matrix is sparsely populated. Moreover, CI cascades are highly asymmetrical. The energy and telecommunication/internet sectors cause most cascading events in other CI sectors (59% and 30% respectively; Table 4). Reversely, not many other CI sectors cause cascade disruptions in the energy, telecommunication, and internet sectors (see Table 3). The affected energy and telecommunication/internet sector event percentages of 34% and 27% respectively (Table 5) are for a large part generated by CI services within these three CI sectors. In short, CI dependencies are very focused and directional. In fact, one has to stop talking about interdependencies, as this suggests a reciprocal relationship that the empirical data set simply does not warrant as occurring frequently, nether in Europe, nor globally. In fact, the database shows only two interdependency events in Europe where loss of medium voltage power transmission affected telecommunications which in turn affected power distribution services: the Italian blackout in 2003 and the Rome mini-telecommunication blackout case. The latter interdependency case has been studied in detail by the EU IRRIIS project (Ciancamerla, 2007).

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International Journal of System of Systems Engineering (IJSSE)

Table 4. Cascade initiated events categorized by initiating sector (percentage of events affecting an affected sector).

	Initiating sector										
Affected sector	Energy	Financial Services	Government	Health	Industry	Internet	Food / Postal	Telecom	Transport	Water	Sample size
Education	33%									67%	3
Energy	89%				4%			**2%**	1%	3%	93
Financial services	18%	18%				9%		55%			33
Food	38%				36%		13%		13%		8
Government	42%		2%	2%	2%	9%		37%	2%	2%	43
Health	65%			12%				18%		6%	17
Industry	80%				7%				7%	7%	15
Internet	24%					23%		53%			79
Postal services											0
Telecom	**49%**				1%	1%		46%	4%		155
Transport	79%		1%		2%		1%	5%	10%	3%	150
Water	68%				20%					12%	25
Total	**59%**	1%	0%	0%	3%	4%	0%	**26%**	4%	3%	**621**

Table 5. Cascade initiated events categorized by affected sector (percentage of events contributed to an affected sector).

	Initiating sector										
Affected sector	Energy	Financial Services	Government	Health	Industry	Internet	Postal & Food	Telecom	Transport	Water	Grand Total
Education	0%			29%						13%	0%
Energy	23%				29%	8%		1%	4%	19%	**34%**
Financial services	2%	100%				18%		11%			4%
Food	1%				10%		50%		4%		1%
Government	5%		25%	14%	3%	10%		10%	4%	6%	3%
Health	3%			57%		2%		2%		8%	2%
Industry	3%				10%				4%	6%	1%
Internet	5%					52%		26%			**10%**
Postal services											0%
Telecom	21%		25%		3%	10%		45%	24%		**17%**
Transport	32%		50%		19%		50%	4%	60%	31%	22%
Water	5%				26%					19%	5%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
# of events	**364**	**6**	**2**	**3**	**18**	**26**	**2**	**159**	**25**	**16**	**621**

This raises an important issue: does this mean that while dependencies and interdependencies are theoretically everywhere, they are rarely strong enough to trigger a serious secondary CI outage which is reported by the news media? Do they only occur after a longer period of disruption of the primary CI than is often the case? Or are these cascading outage events so hidden in the chaos caused by the primary CI outage that the secondary effects have no news value to the press?

The dependency of many CI sectors on energy and telecommunications has been reported widely. Our analysis suggests that the dependency on energy is substantially higher (taken mitigation measures into account) as 59% of all cascades originate within the energy sector, 30% in the telecommunication and internet sectors, and 4% in the transport sector, 3% in the water sector, and 4% in the remaining sectors.

4.3 Energy and Telecom sector services

The energy sector column in **Table** 4 shows that the energy sector is an important cascade initiating sector for almost all sectors. The second largest is the telecommunication sector. When we consider the energy sector services in Europe, it can be concluded that CI cascade initiating events for a large majority originate within the electrical power service (see **Table 6**). It can be deducted that serious disruptions of electric power have affected almost all CI sectors and services. Within the energy sector, 83 dependencies exist internal to the power sector (e.g. distribution dependent on power generation and power transmission). Only four cases were found where district heating failed due to power generation and distribution failures; gas distribution was affected only once.

The telecommunication services fall apart in the backbone networks and a wide array of telecommunication services such as cable/CATV services, the fixed telecommunication system (e.g., POTS, ISDN, DSL-services, leased line services, alarm line services), mobile telephony, and mobile data including SMS. As the telecom sector column in **Table** 4 indicates, the telecommunication sector is an important initiator for cascading events in the financial services sector, the government services sector, and the internet and the telecommunication sectors themselves. Due to the telecommunication sector structure, disruptions of backbones more seriously affect internet services than other telecommunication services. In the same way, the loss of cable services affects the access to internet and voice (over CATV and IP) services to citizens.

Detailed analysis of the CI disruption database shows that the financial sector only seems to be affected by disruptions in the fixed telecommunications infrastructure as that affects the functioning of automated teller machines (ATM) and electronic payments. No other reports about affected financial sector services have been found. Also the 1-1-2 and other emergency response services are affected by fixed infrastructure failure.

As most mobile telecommunication transmission between base stations (antennas) and the base station controllers (BSC) often use the fixed telecommunication infrastructure, it is not surprising that fixed telecommunication disruptions in Europe immediately has a cascading impact on the GSM/UMTS services.

Table 6. Cascade initiated events categorized by CI sector service (percentage of events contributed to an affected sector).

		Initiating sector									
		Energy Sector				Telecommunications Sector					
		Electric Power	Gas	Oil	Energy # of events	Backbone	Cable / CATV	Fixed telecom	Mobile telephony	SMS	Telecom # of events
Affected sector	Education	33%			**1**						**0**
	Energy	68%	16%	3%	**81**			3%			**2**
	Financial services	18%			**6**	6%		45%			**17**
	Food	38%			**3**						**0**
	Government	40%	2%		**18**	2%	2%	26%	7%		**16**
	Health	65%			**11**		6%	12%			**3**
	Industry	80%			**12**						
	Internet	24%			**19**	28%	11%	14%			**42**
	Postal services				**0**						**0**
	Telecom	48%	1%		**76**	12%	2%	28%	3%	1%	**71**
	Transport	77%	1%	1%	**118**			3%	2%		**7**
	Water	68%			**17**						**0**
	Total %	55%	3%	1%	61%	7%	2%	14%	2%	0%	25%
	# of events	**340**	**16**	**4**	**362**	**44**	**14**	**88**	**11**	**1**	**158**

4.4 *Escalation of cascades*

The domino theory suggests that CI failures rarely occur in isolation. Or in other words: once a serious disruption occurs in a CI, disruptions in other dependent CI services follow. Cascades would then be more comprehensive than one outage triggering one other outage. **Table 7,** however, shows that on average a cascade initiating event in the energy sector in Europe triggers 2,0 disruptions in other CI services ('cascade fan-out'). A cascade initiating event in the telecommunication sector on average triggers a little over 2,1 disruptions in other CI services.

Considering all events (including all independent events), **Table 7** also shows that an event in the energy sector or in the telecom sector in Europe on average triggers in half of the cases a disruption in another CI. On average over all CI sectors in Europe, a CI disruption event triggers in three out of ten cases a disruption event in another CI service.

As power and telecommunications in the USA are more often affected by bad weather than in Europe, companies and consumers seem to be less affected by CI outages – at least according to the news sources. More resilience measures by companies and citizens such as backup power generators seem to be in place on the one hand. On the other hand, US companies and citizens probably are used to services that are disrupted a couple of times a year for a couple of days. It can not be a surprise to find that a disruption event in the energy sector in the USA on average triggers only in one out of five case of the cases a disruption in another CI. Telecommunication on average triggers in half of the cases a disruption in another CI, which is comparable to the findings for

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International Journal of System of Systems Engineering (IJSSE)

Europe. The energy sector in the USA has an average cascade fan-out of 1.8 disruptions which is 10% less than in Europe (sample size=410 cases). The US telecommunication sector has an average cascade fan-out of 1,9 disruptions which is also some 10% less than the Europe figure (sample size=183 cases). When considering all US CI sectors, a CI disruption event causes in two out of ten cases a disruption event in another CI service.

Table 7. Categorization of number of CI events (absolute # of events CI sector to sector).

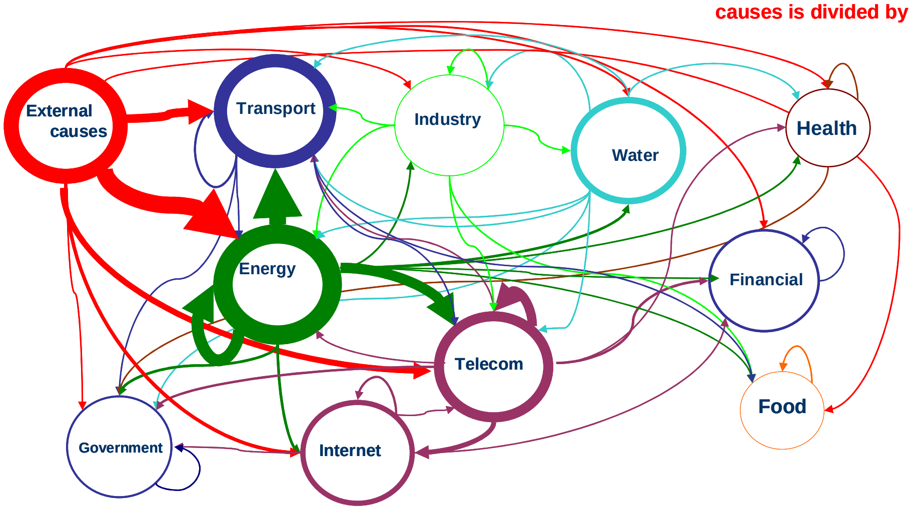
Initiating sector	Avg. # of resulting events if cascading	Sample size	Avg. # of resulting events (all events)	Sample size
Education		0		4
Energy	2,0	174	0,50	708
Financial services		3	0,06	94
Food		1	0,07	14
Government		2	0,03	72
Health		1	0,02	44
Industry		7	0,59	29
Internet	1,2	22	0,13	204
Postal		1		1
Telecommunications	2,1	87	0,50	368
Transport	1,3	20	0,05	468
Water	1,6	10	0,16	97
Total	1,9	328	0,30	2103

Of the 2103 events, 534 (25%) events are a first level cascade resulting event. Only 83 events (4%) are a second level cascade resulting event, and 4 events (two times power distribution, two times railway transport) are at a third level cascade resulting event. This means that cascading events dampen out fast and propagate far less deep than the domino theory often suggests.

4.5 CI dependency graph

Rather than using the numbers and percentage tables above, we brought together these figures in a single figure (Figure 1) covering the period January 2005 till May 2009. The line thickness is relative to the number of external or dependency events. The number of external causes is divided by five to derive the line thickness. It will be obvious that in Europe the database shows that energy, telecommunications & internet, and transport are the key critical infrastructures which disruptions are reported on in news reports. This set of empirical data of serious CI outages shows a different view than (Rinaldi, Peerenboom, and Kelly, 2001). They showed also weak dependencies where physical effects, buffering, and alternate modalities cause cascading – if occurring at all – in practice may have less serious impact than suggested.

Fig. 1. CI disruptions: external versus dependency causes (Europe 2005 - May 2009)



Relative size of external causes is divided by five

4.6 *CI disruptions in Europe per month*

As CI disruptions may correlate with seasonal influences, the authors analyzed the European 2005 – 2009 CI disruption data (see Figure 2). Some seasonal effects seem to be present, although deeper analysis is required in future. The energy disturbances are somewhat skewed by the major impact of the November 4, 2006 European-wide outage event. Apart from that, one can notice energy disruption peaks in November and January (winter storms) and July (lightning, heat waves, and forest fires) affecting the energy sector. The various transport modalities are mostly affected by both power outages and extreme weather conditions. The July peak in transport relates to the power dependencies, the terrorist attacks on transport means in Germany and in London in 2005, and the flooding in the UK in 2007.

Of interest is the fact that in technology-oriented CI less disturbances occur in December than in November and January. This may be related to the fact that less construction work and system reconfigurations occur in December which cause disruption of power, gas, and telecommunication and internet transmission services.

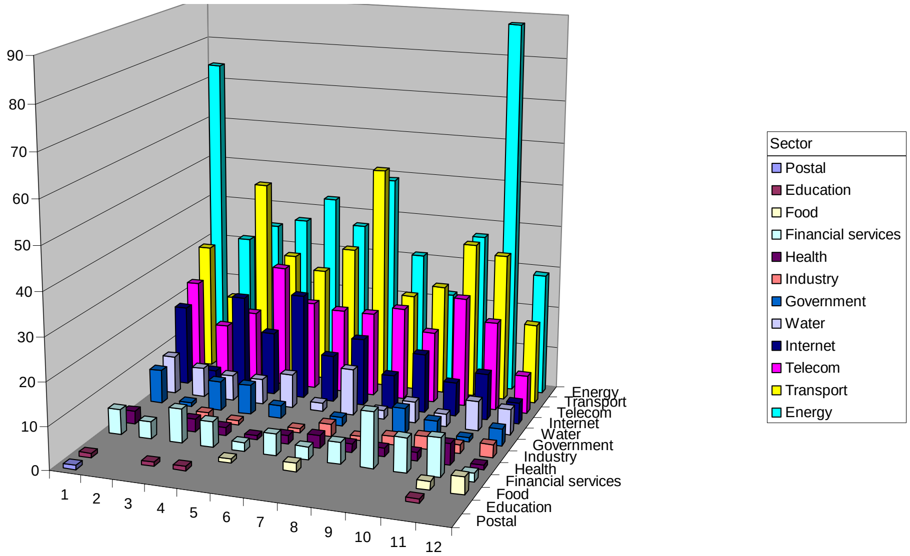


Fig. 2. CI outages per CI sector per month (Europe 2005-2009)

5. Conclusions

Our findings raise several important issues. First, while the current literature gives very little clues as to the probability of cascading failures, our empirical data suggests that such cascades are in fact fairly frequent. This stands in stark contrast to the typical examples of events of low probability and high consequence that are often presented as evidence of the urgency of dealing with CI dependencies. CI cascading failures are at once more banal and more frequent.

Second, the findings question the validity of the CI domino theory. While there are an almost unlimited number of dependencies and interdependencies among CI possible, i.e., there are many pathways along which failures could propagate across CI sector boundaries, the authors found that this potential for cascades is not expressed in the empirical data on actual *serious* events. The cascades that were reported were highly asymmetrical and focused. The overwhelming majority of them originated in the energy and telecommunication sectors. The finding that these two sectors generate the most cascades is not unexpected. What is new is the fact that so few cascades took place in other CI sectors.

Third, interdependencies far less occur than dependency analysts have consistently modeled. Only two interdependency cases have been found on a total of some 2100 European CI disruption events, and none are present in the other 2425 events which occurred outside Europe. In short, while CI dependencies and interdependencies are everywhere, they rarely appear to be strong enough to trigger a reported *serious* CI outage. It is unclear whether this is because the CI operators manage the (inter)dependencies effectively or because the dependencies are not that powerful to begin with. In any case, it seems that CI are either more loosely coupled than the CI domino theory suggests, or that the CI dependencies occur at a more technical level not becoming visible to news reports.

Of course, there are a couple of qualifications that go with this conclusion. First of all, our findings do not rule out the possibility of multi-sector failure – i.e., we still face the possibility of scenarios of low probability and high consequence. Second, even if the CI domino theory is misleading, that does not negate the fact that the damage resulting from cascades initiated by the energy and telecommunication sectors can be substantial. The third implication of our analysis is that it does not support the idea that CI dependencies are "the unmanaged challenge." While there is an intuitive appeal to this idea, it may in fact be a myth. If we assume a vast web of dependencies that can trigger cascades, then it seems inevitable that society ends up with a shortfall in the governance of this risk. But the evidence suggests that even if we assume this shortfall to exist, it does not translate into actual cascades. The cascades that we do find point to dependencies that are anything but unmanaged. Nevertheless, governance is needed. For instance, the high reliability of electricity and other critical services is anything but guaranteed in Europe. Moreover, those CI sectors that depend on the energy and telecommunication sectors can improve their strategies to manage those dependencies. Especially, the collected data suggest that CI dependencies in non-normal mode of operation are less well understood and therefore managed than required (Nieuwenhuijs, Luiijf, and Klaver, 2008). For example, during one incident backup power generators did initially manage to prevent a cascade, but they later failed because the depending CI sector was unable to organize the transport and refilling of diesel fuel for resupplying the generators. In other words, these dependencies require continual efforts to mitigate their impacts, but they are hardly "the unmanaged challenge." In sum, the sobering conclusion emerges that CI cascading dependencies are focused to a limited number of CI sectors, occur more frequently than expected, and do not often cascade deeply.

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References

Auerswald, P.E. 2006. 'Complexity and Interdependence', in P.E. Auerswald, L.M. Branscomb, T.M. La Porte, E.O. Michel-Kerjan (eds.), *Seeds of Disaster, Roots and Response: How Private Action can Reduce Public Vulnerability*, Cambridge: Cambridge University Press, pp. 157- 163.

Ciancamerla, E. Minichino M., A mini, Telco-blackout impacting other infrastructures, including ACEA power grid in IRRIIS internal report. 2007, ENEA.

European Council, European Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection, Brussels, December 2008.

Von Kirchbach, H-P. et al, Bericht der Unabhängigen Kommission der Sächsischen Staatsregierung Flutkatastrophe 2002, 2003.

Nieuwenhuijs, A.H., Luiijf, H.A.M., Klaver M.H.A., "Modeling Critical Infrastructure Dependencies", in: *IFIP International Federation for Information Processing, Volume 290, Critical Infrastructure Protection II*, eds. P. Mauricio and S. Shenoi, (Boston: Springer), October 2008, pp. 205-214.

Pederson, P., Dudenhoeffer, D., Hartley, S. and Permann, M., Critical Infrastructure Interdependency Modeling: A Survey of U.S. and International Research, 2006.

Rinaldi, S.M., Peerenboom, J., Kelly, T., Complexities in identifying, Understanding, and Analyzing Critical Infrastructure Dependencies, Special issue IEEE Control Systems Magazine on "Complex Interactive Networks", December 2001.

Simonoff, J., Restrepo, C., Zimmerman, R., Naphtali, Z., "Analysis of Electrical and Oil and Gas Pipeline Failures", in: Critical Infrastructure Protection edited by E. Goetz and S. Shenoi, IFIP WG 11.10 series in Critical Infrastructure Protection, 2008.

Svendsen, N.K., and Wolthuysen, S.D., Connectivity models of interdependency in mixed-type critical infrastructure networks, Information Security Technical Report Vol 12, No 1, pp 44-55, Elsevier, ISSN 1363-4127, 2006.

TNO's critical infrastructure disruption database, version 217, 14 June 2009.

UCTE, Final report – System Disturbance on 4 November 2006, UCTE, 2006. On-line: http://www.ucte.org/_library/otherreports/Final-Report-20070130.pdf

Zimmerman, R., Restrepo, C., The next step: Quantifying infrastructure interdependencies to improve security, International Journal of Critical Infrastructures, vol 2(2-3), pp 215-230, 2006.