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Coordination Dynamics in Disaster Response Operations: A Network Based Discrete Event Analysis

Nadia Saad Noori

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5 Research Results

In the previous chapters we presented a combination of concepts and theories used to develop a method for analyzing coordination dynamics in disaster response network. The method included (1) collecting data on disaster incidents by adopting a case study approach, (2) conducting a qualitative analysis of those incidents using textual analysis and coordination theory, (3) quantifying the outcomes of the qualitative analysis using SNA and community detection algorithms, and (4) constructing Colored Petri Nets (CPNs) by transforming extracted information from the coordination matrices and SNA to model the coordination flow in disaster response networks.

The results showed the method capabilities to analyze complex large-scale and simple small-scale incidents. In addition, the methods provided different levels of granularity in analyzing coordination-clusters in disaster response networks (local vs. global view). The Elbe River Flood case tested the methods for its ability to handle complex large-scale disasters, thus a global view was created. In comparison, the Schiphol Tunnel Fire case tested the method accuracy in analyzing coordination dynamics in a small-scale incident, thus a local view was needed. The case analysis shows the method's capabilities in having a local view of coordination dynamics inside teams in relation to their global position inside a greater response network.

The following sections of this chapter contain a presentation of the results after applying the proposed methodology to the selected case studies (i.e. Elbe River Flood and Schiphol Tunnel Fire). The first section of this chapter covers results of extracting coordination-clusters by applying the Louvain algorithm to the time-based response networks from the case studies. The second section covers further results related to types of emerging coordination-clusters in the response networks. The third section shows results of patterns of emerging influencers in coordination-clusters by tracing the centrality values of participating units. The final section in this chapter covers results from transforming the networked operations into an event-based dynamic presentation using Hierarchical CPN to model the coordination flow in the response operations.

5.1 Emerging Hierarchies of Coordination-Clusters

The next step following the construction of response networks for both the Elbe River Flood and the Schiphol Tunnel Fire is to apply the Louvain method (Blondel, et al., 2008) to extract coordination-clusters in those networks. In Section 3.2.2, Chapter 3 we mention that Resolution *Factor* value (range from 0 – 100,000) control granularity of clusters detected in Pajek Software. The default value is 1 and higher values result higher the number of clusters in the network. In the analysis, we applied different values the *Resolution Factor* to investigate the affect of changing the levels of clustering granularity. Various range of values were tested to examine the changes in the cluster formation. Table 22 shows the results from applying Louvain method with values of 0.5, 1.0, and 1.5 of resolution factors for the initial organizational response network at T_0.

The different values for resolution factors helped to examine the variants in the network structure and the emerging hierarchies in every case. As we mentioned earlier, changing the resolution factor changes the size of the community detects. The default value is 1, and values more than one result less number of communities and smaller community size, while values less that one would produce high number of communities and larger community size.

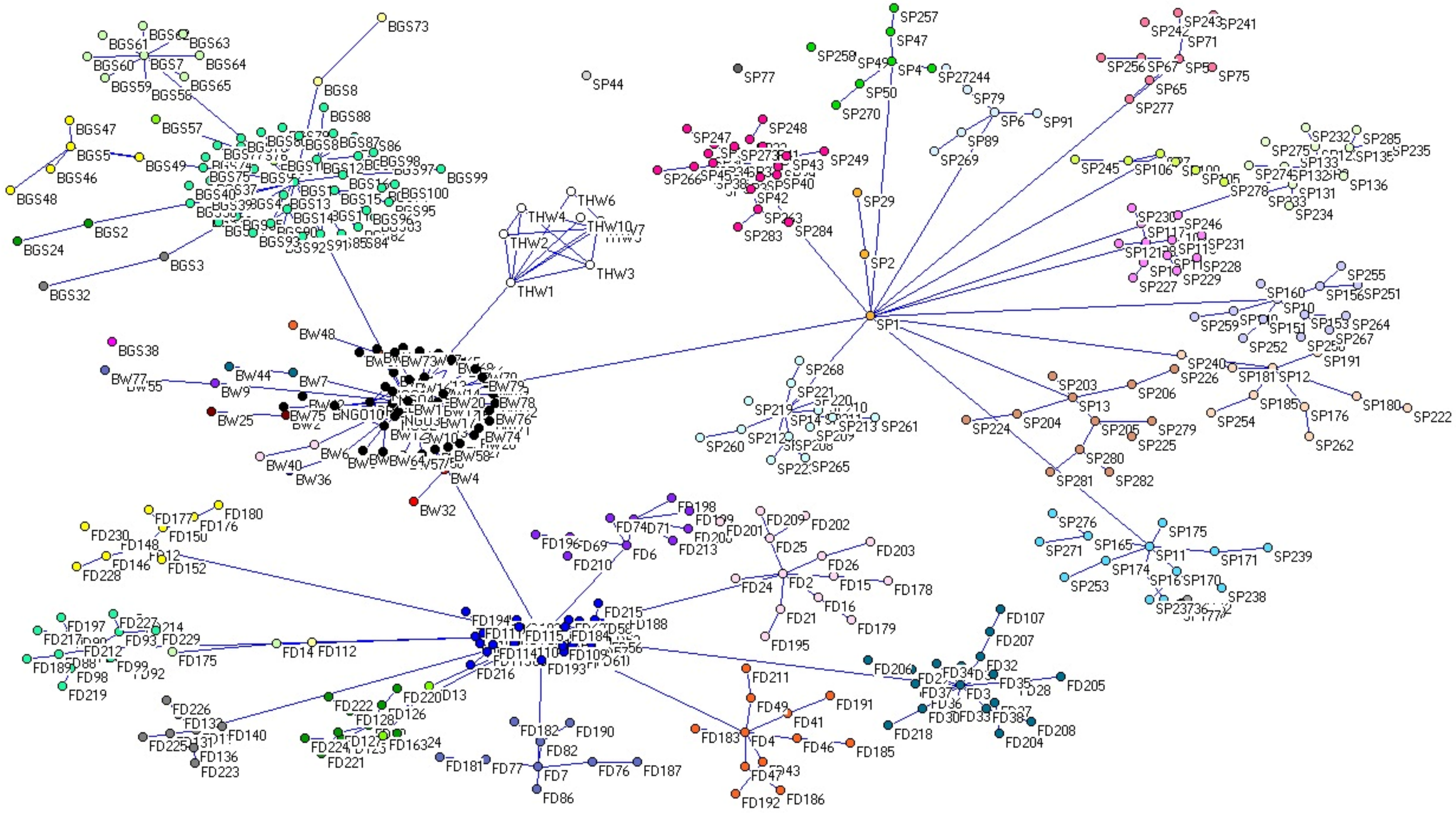
Resolution Factor	Number of clusters	Modularity
0.5	45	0.928
1.0	56	0.904
1.5	61	0.886

Table 22. The values of resolutions factors and associated values of modularity and number of clusters for the initial network at T_0.

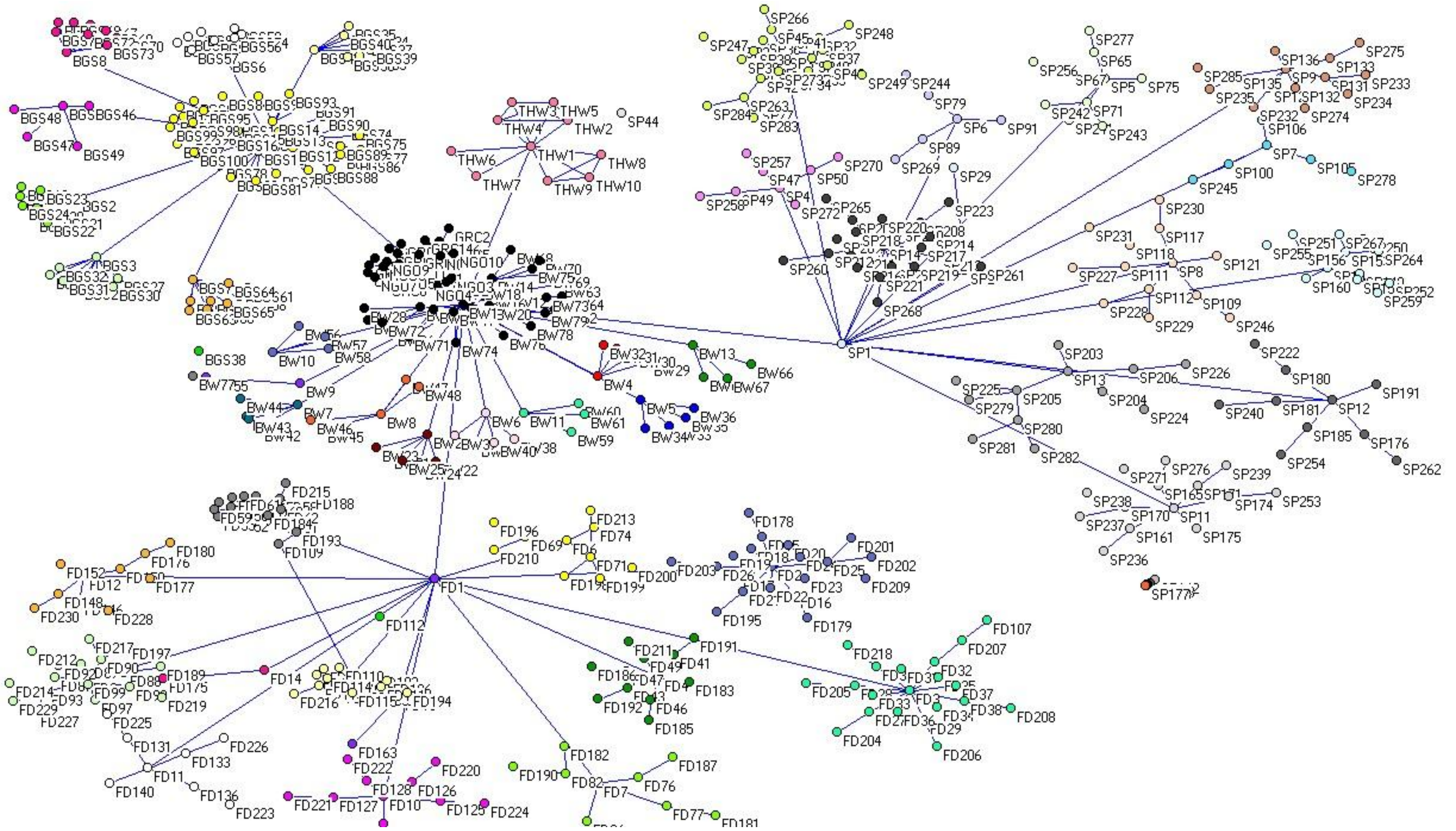
The Initial Network was created based on divisions' distribution in each organization engaged in the response operations for Day 1, T_0. The original graph of the network is shown in Figure 50.

When applying the clustering method to the initial network with resolution value of 1, the formation of the clusters reflected the original organizational hierarchy of involved parties. The hierarchical structure of the organization created multi-tiered networks inside the original network. Example of that, if we look at the Saxon Police cluster (SP) in Figure (62-a Resolution Factor =1.0), there are 13 clusters forming. The number 13 matches the number of districts in Saxony and it is linked to our assumption of having a main police HQ in every district in Saxony. So number of cluster is aligned with the hierarchical structure in this case. In another example, we can look at the Fire Department nodes (FD). There are 12 clusters formed based on the division assumed in Table 17, which follows the hierarchical structure of the FD command and control structure. The same apply for the rest of the organizations where the cluster formation is a reflection to the hierarchical structure of each organization.

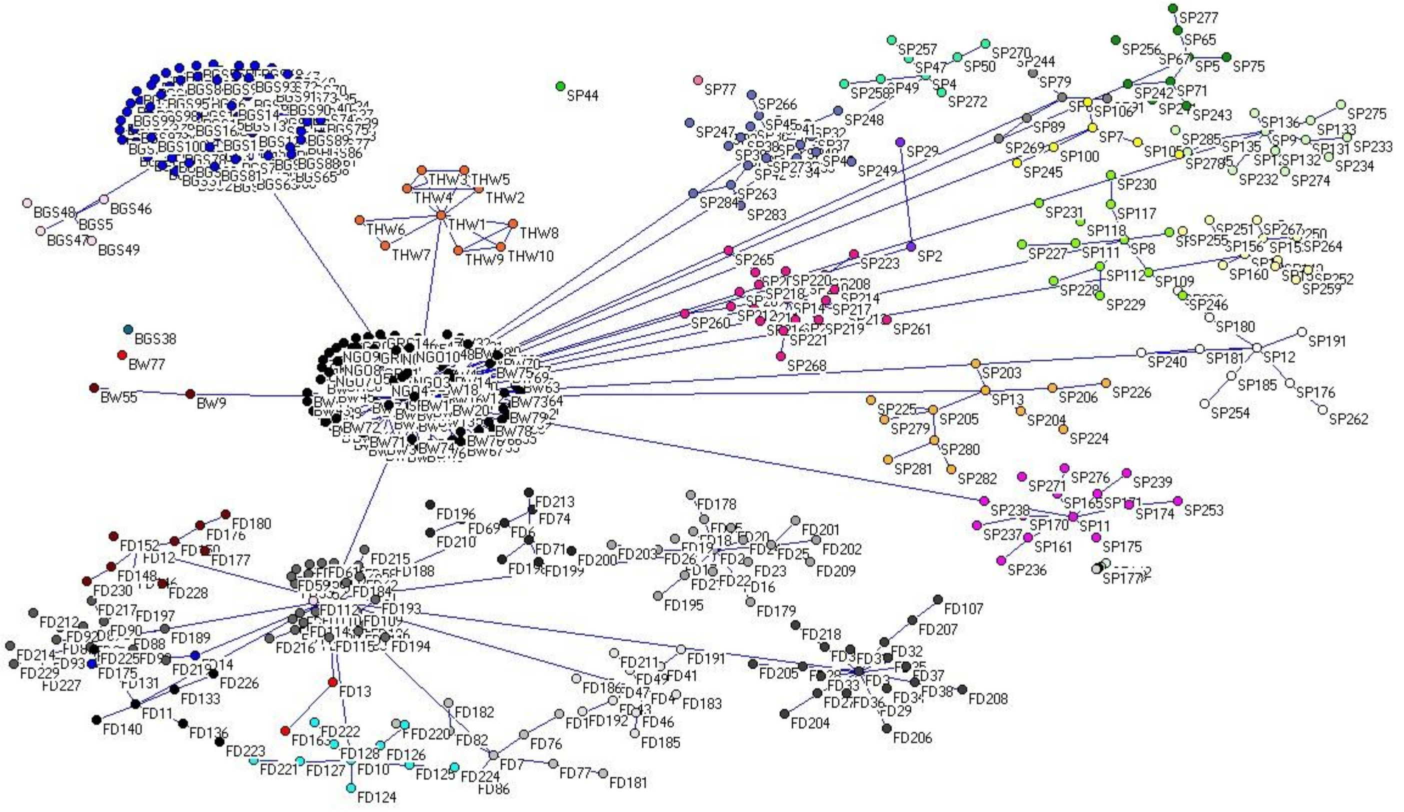
When using resolution values of 1.5 and 0.5, the clusters remained to follow the organizational structure but more tiers of the hierarchy either was expressed (in case of 1.5 value) or suppressed (in case of 0.5). The network graphs in Figures 61-b and 61-c show an example of the difference between the clusters formation in both cases. The BW clusters start with one large cluster for resolution values of 0.5, then the number increases to 6 cluster for resolution value of 1, and finally 11 clusters with resolution value of 1.5.



a. Resolution Factor = 1.0

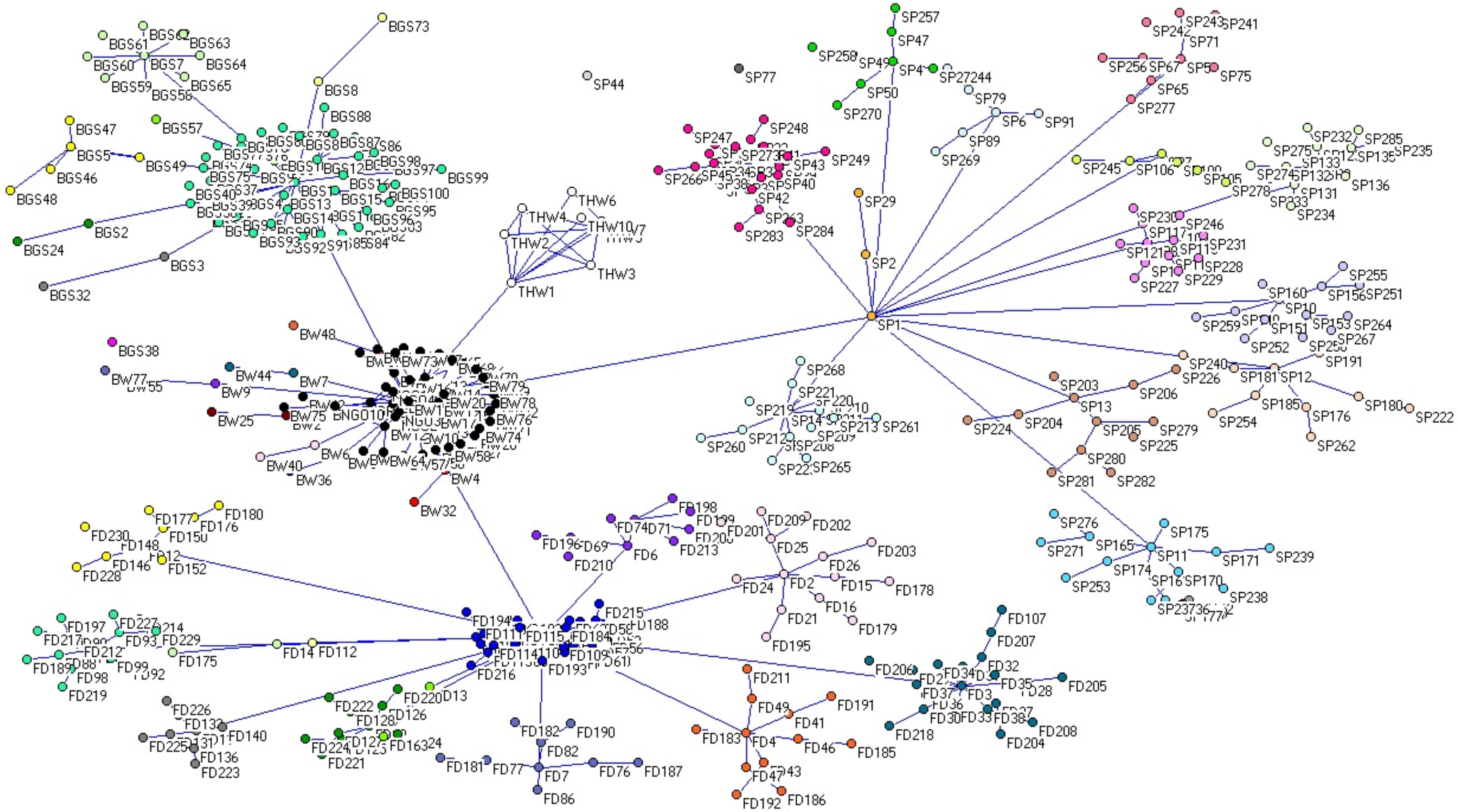


b. Resolution Factor = 1.5

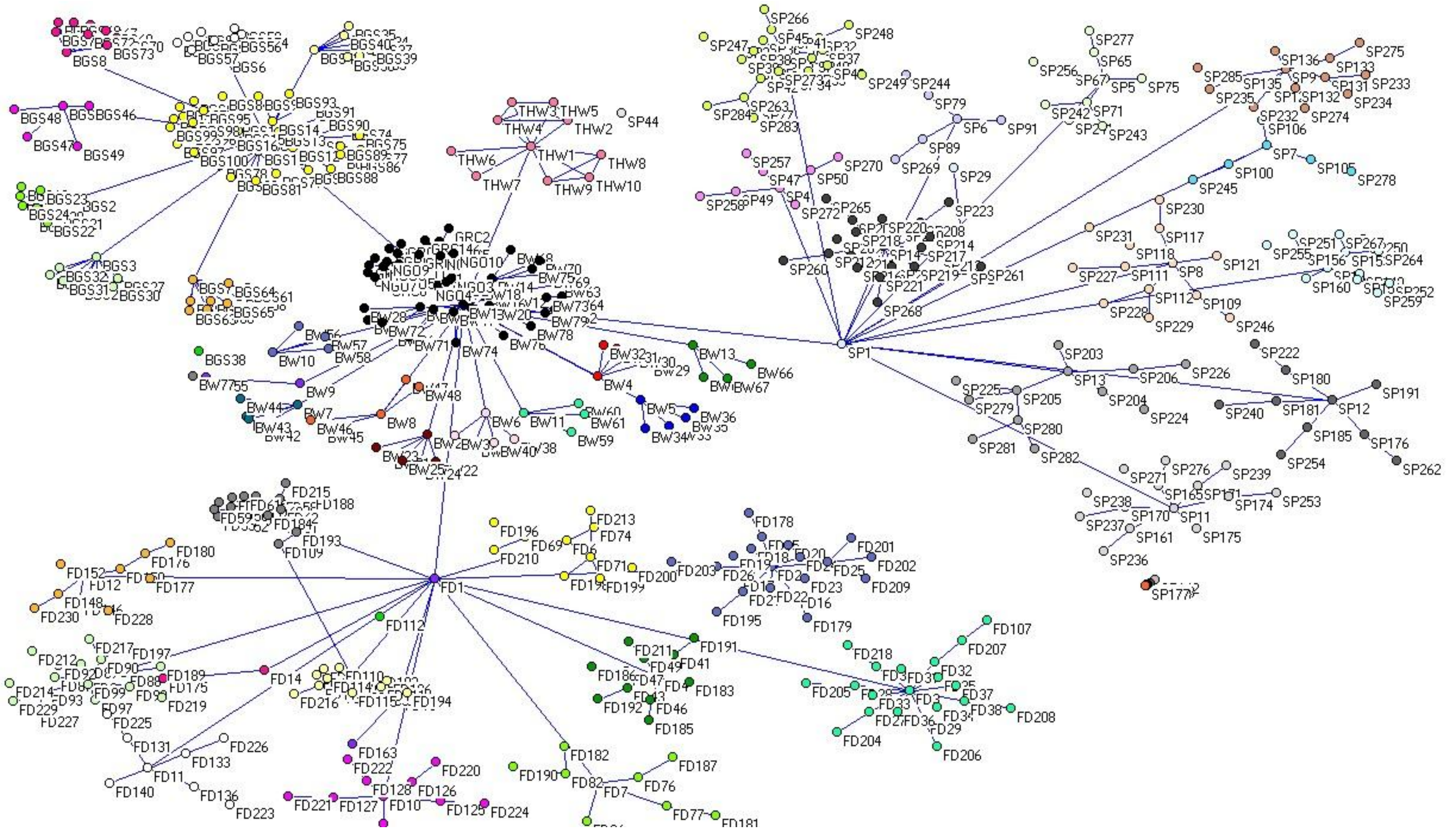


c. Resolution Factor = 0.5

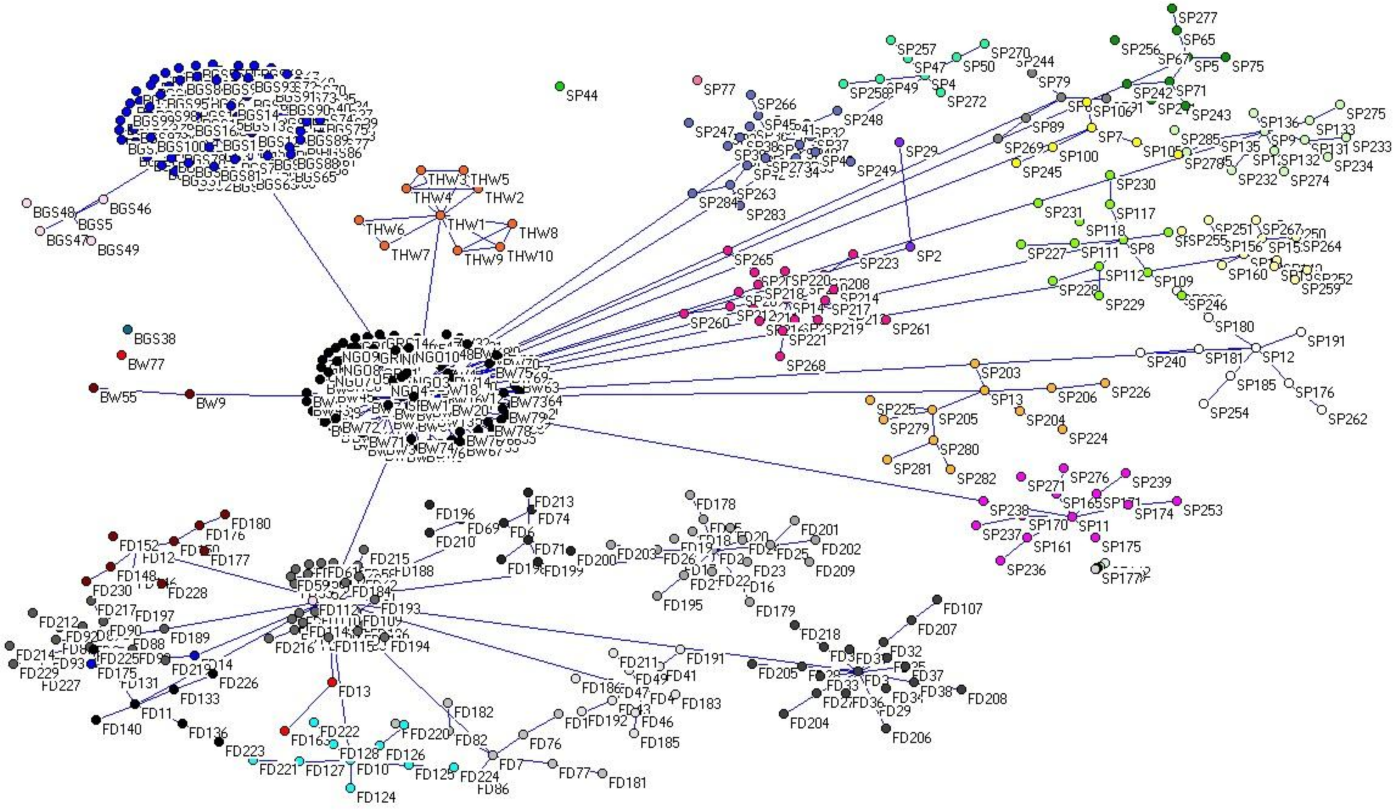
Figure 61. The initial network at T_0 graphs with the different resolution factors.
The higher the Resolution Factor, the more we can notice the original hierarchical structure of the network.



a. Resolution Factor = 1.0



b. Resolution Factor = 1.5



c. Resolution Factor = 0.5

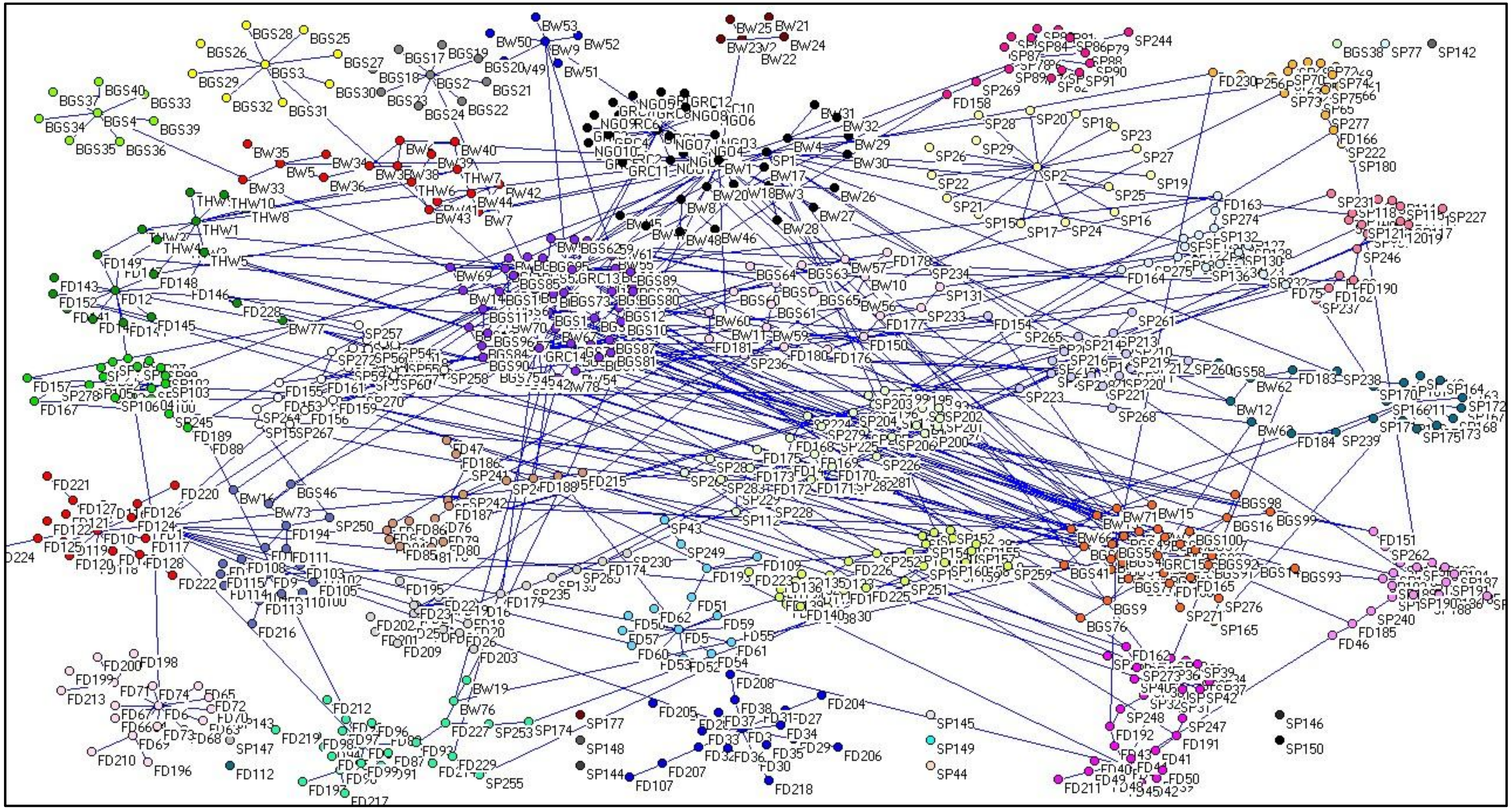
Figure 61. The initial network at T_0 graphs with the different resolution factors. The higher the Resolution Factor, the more we can notice the original hierarchical structure of the network.

After analyzing the Initial Network of T_0, we applied the same procedure to the response network of T_1 shown in Figure 50. The same values of the resolution factor were used (i.e. 0.5, 1.0 and 1.5) and the results are listed in Table 23.

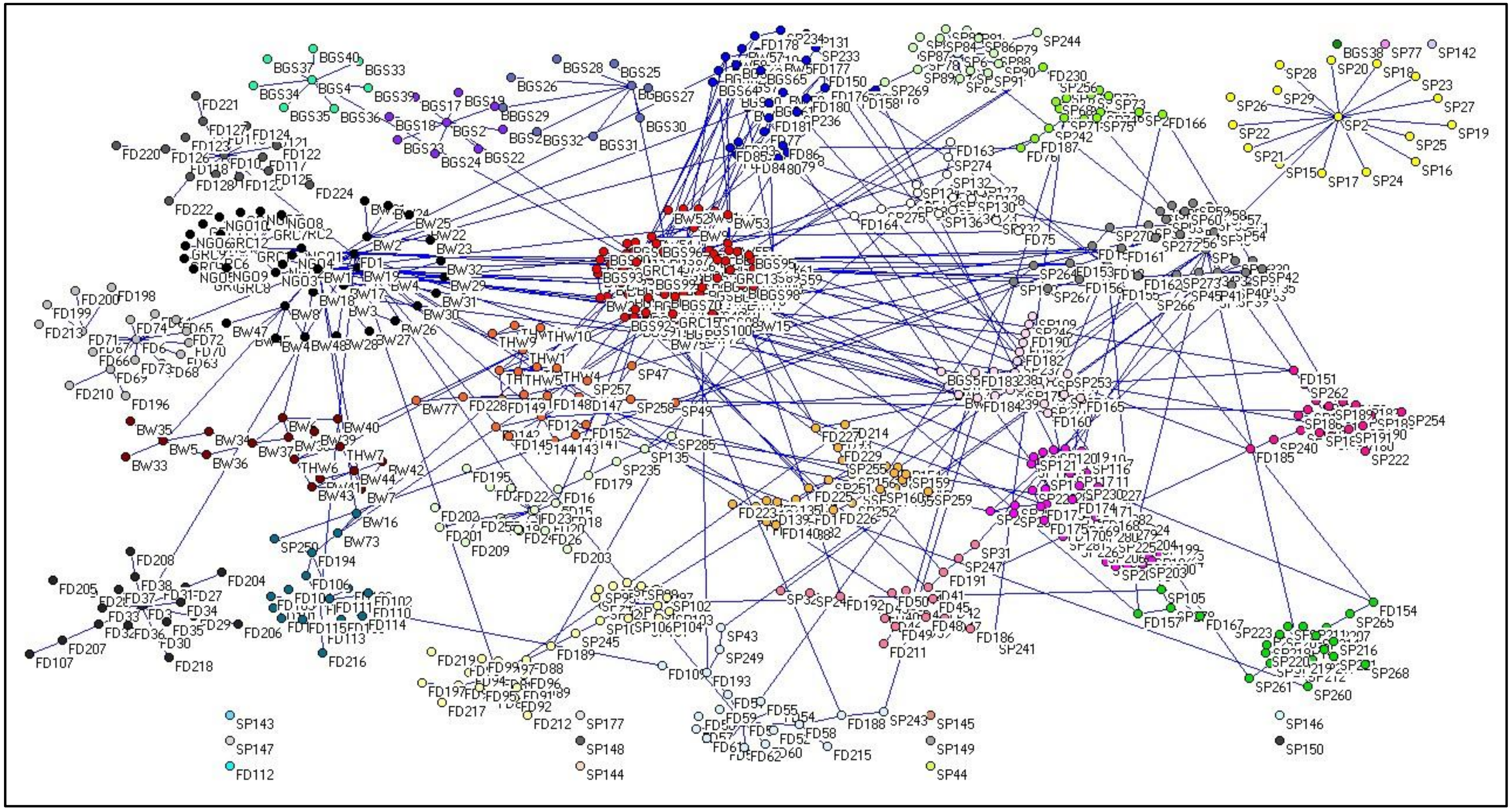
Resolution Factor	Number of clusters	Modularity
0.5	31	0.810
1.0	40	0.762
1.5	46	0.730

Table 23. The values of the resolutions factors and associated values of modularity and number of clusters for the collaboration network at T_1.

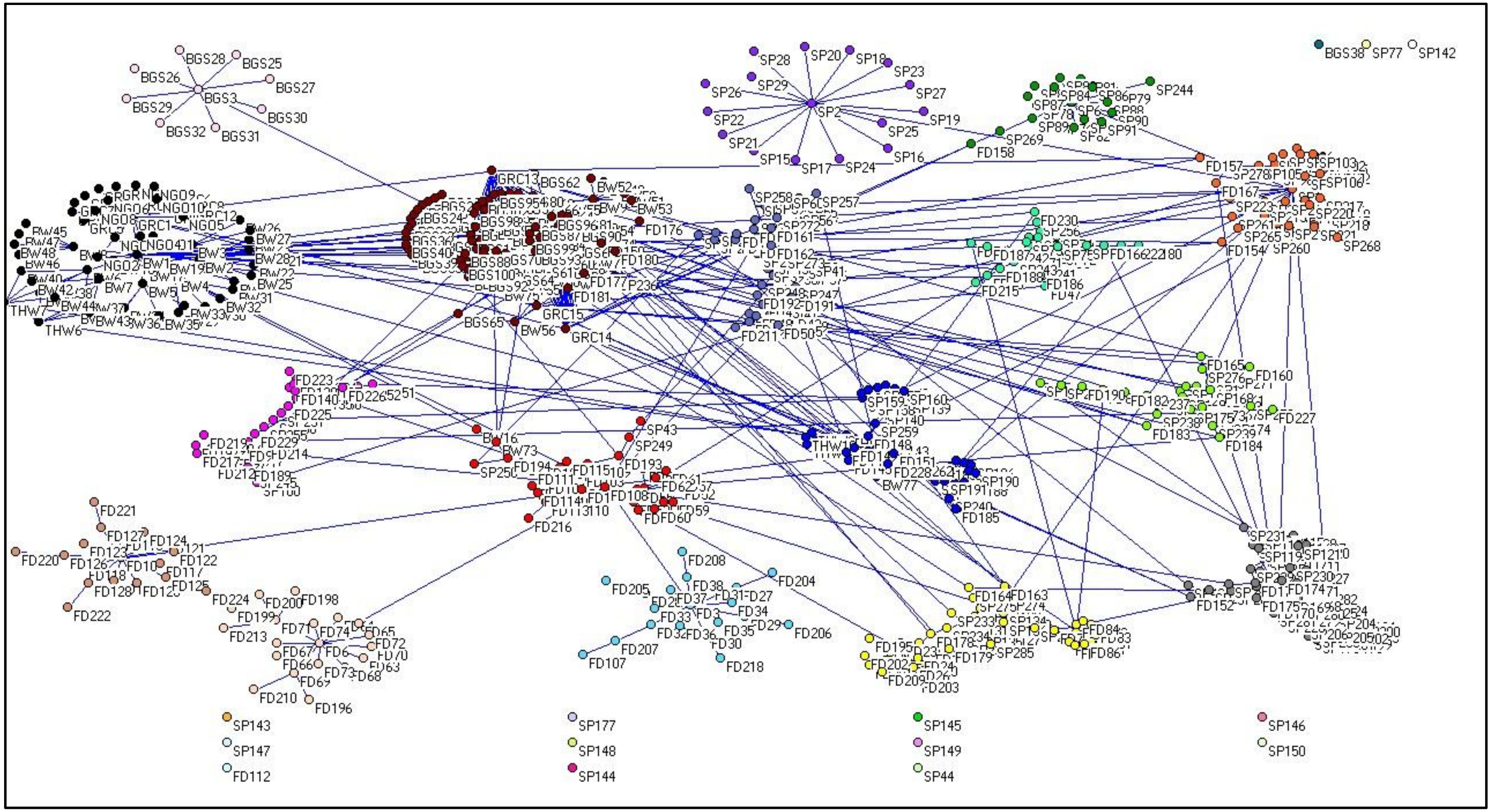
In comparison with Table 22, the results in Table 23 show a decline in the number of the clusters and the values of modularity for similar values of resolution factor. Such decline is a result of new connections created in the response network. Those connections are based on data from the coordination matrix for Day 1 and units distribution listed in Table (18) and Table (19). The decline in the modularity and cluster numbers reflects the breakdown in the hierarchical structure of the initial network. This breakdown is a sign of change in the organization behavior under the stress created by the disaster environment. The breakdown of the hierarchical structure of the network can be seen in the graphs in Figure 62 of the response network at T1 after applying the cluster analysis.



a. Resolution Factor = 1.5



b. Resolution Factor = 1.0



c. Resolution Factor = 0.5

Figure 62. The response network at T_1 with the different resolution factors.

5.2 Task –Based Coordination-Clusters

After applying the clustering method (i.e. Louvain community detection) to extract the coordination-cluster in each response network at Tx, we examine the coordination dynamics of the response operations. In order to do so, we trace the formation of the different clusters and look up links between the units involved in a same cluster. Figure 63 and 64 show the evolution of coordination-clusters in the Schiphol tunnel network at T0 (0-15min) and T1 (16-30min). In Figure 64, we see four clusters forming with different tasks like fire investigation by fire fighters in fire extermination cluster or securing airport perimeter by Office of Koninklijke Marechaussee-Dutch Royal Police (KMar_O) in security & safety cluster. In Figure 64, we see the emergence of different functional clusters, new actors' engagement, and redistribution of actors within the coordination-clusters. For example, KMar_O node moved from security and safety operations cluster (at T0) to platform evacuation cluster (at T1). A new actor joint, NS_Passengers, platform evacuation cluster in response to functional requirement at T1.

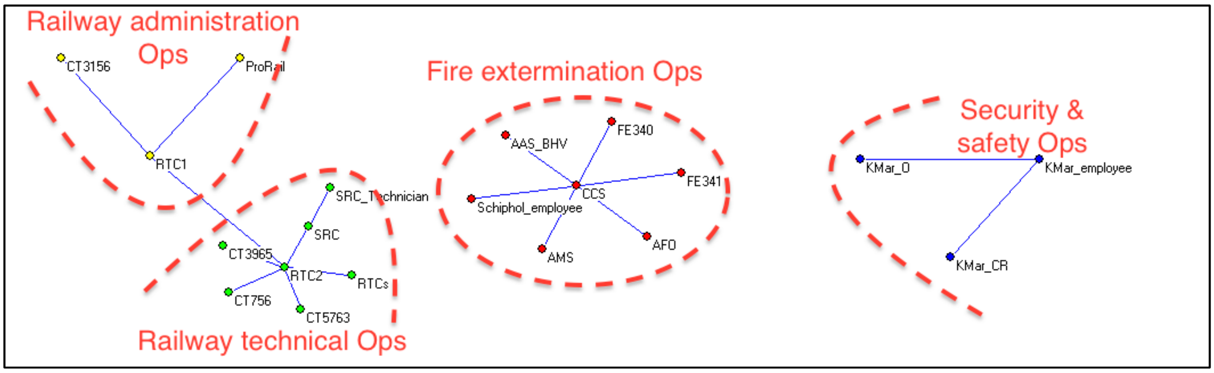


Figure 63. Schiphol Tunnel Fire response network at T_0

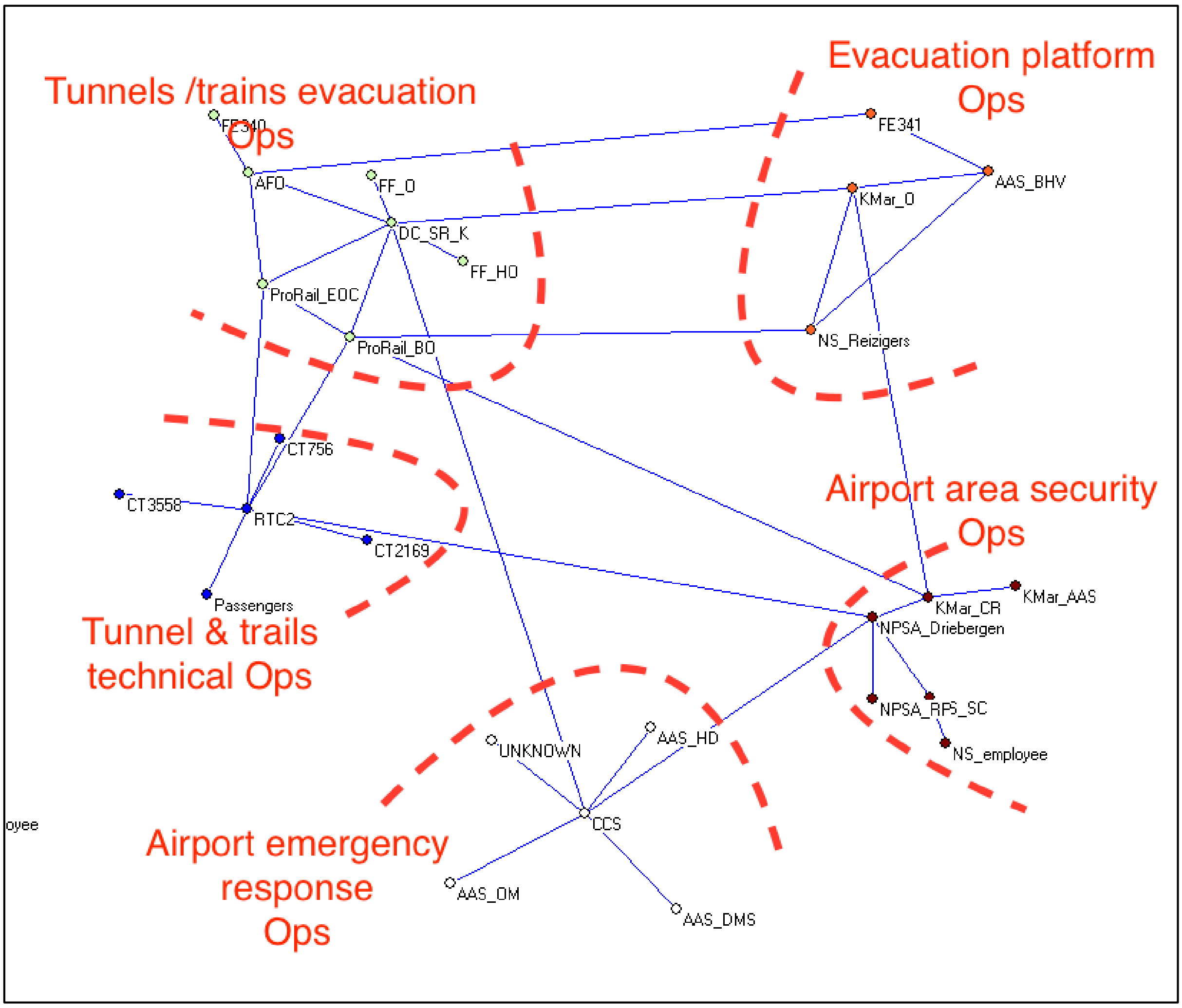


Figure 64. Schiphol Tunnel Fire response network at T_1

In the 2002 Elbe River flood response network, we noticed similar patterns of clusters formation to the ones of Schiphol tunnel fire. For example, in Figure 65 we see formation of a high number of clusters with dike enforcement at T1 that reflects a requirement of such task over the affected areas in the Free State of Saxony. At T2, water levels had risen to unexpected levels that introduced new tasks like search and rescue, evacuation beside dike enforcement. Therefore, in Figure 66 the number of clusters increased sharply due to the rapid expansion of the flooded areas in Saxony. At T2, a regional catastrophe status was declared; therefore, we notice engagement of new forces and organizations such as Federal Border Police (BSG) and German Red Cross (DRK) to cope with the increasing requests for more forces and responding to new tasks.

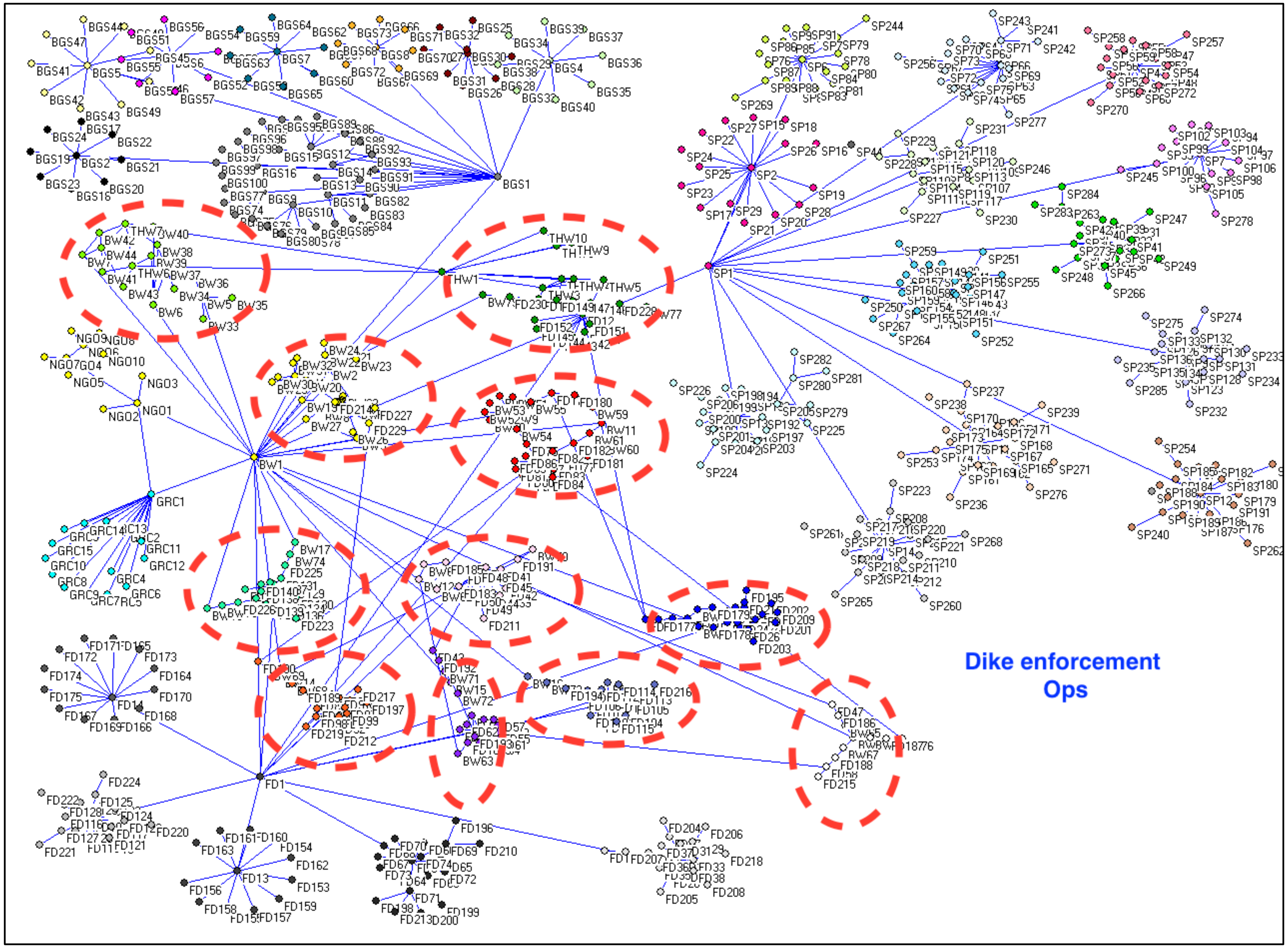


Figure 65. Elbe River Flood response network at T_1

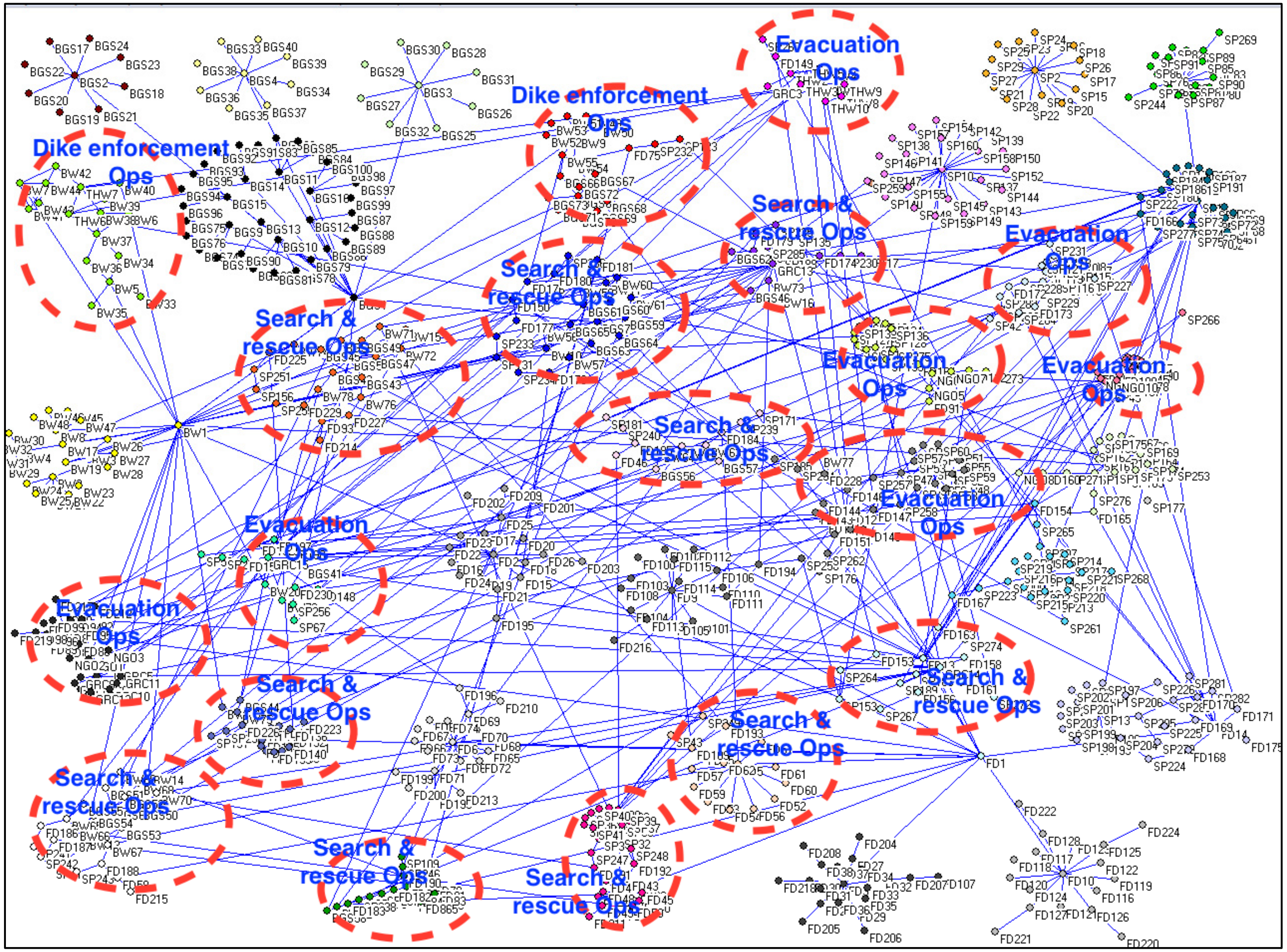


Figure 66. Elbe River Flood, response network at T_2

5.3 Homogenous vs. Heterogeneous Coordination-Clusters

In Figure 67 we can see the formation of two types of clusters. First type is *a homogeneous cluster* represented by a group of entities (units or divisions) that belongs to the same organizations and kept its hierarchal position in the network. Second type is a *heterogeneous* cluster represented by a group of entities that belongs to different organizations in the response operations but performing similar tasks. We took a closer look at the heterogeneous clusters and we found that the clusters are a representation of a task (e.g. search and recue, clearing debris, or enacting tents) but the numbers of the clusters did not represent the number of the tasks performed. The number of clusters was a representation of the collaboration teams within each task. Another observation was that heterogeneous clusters were mainly forming at the lower crisis management levels of the German system, as we move up in the system, the clusters become more homogeneous. However, we can see that in both Figures 67 and 68 that coordination-clusters still follow the distribution of divisions in Table 17.

In Figure 68 we have 12 clusters, 5 clusters included a mix of organizations and 7 clusters (encircled with a dotted red line) include only Saxon Police (SP) and Fire Departments (FD). The FD-SP clusters are a sign of the close collaboration between the Fire departments and the Saxon Police on the lower level of the crisis management authorities. The fact that “higher Levels of crisis management authorities” had declined to declare the state of emergency on Day 1 of the flood; it forced police and firefighters from various townships to collaborate and perform various tasks in response to the unfolding disaster events. Such delay in the decision-making process during critical time is another reason behind the breakdown of the hierarchy that was mentioned in section 5.1.

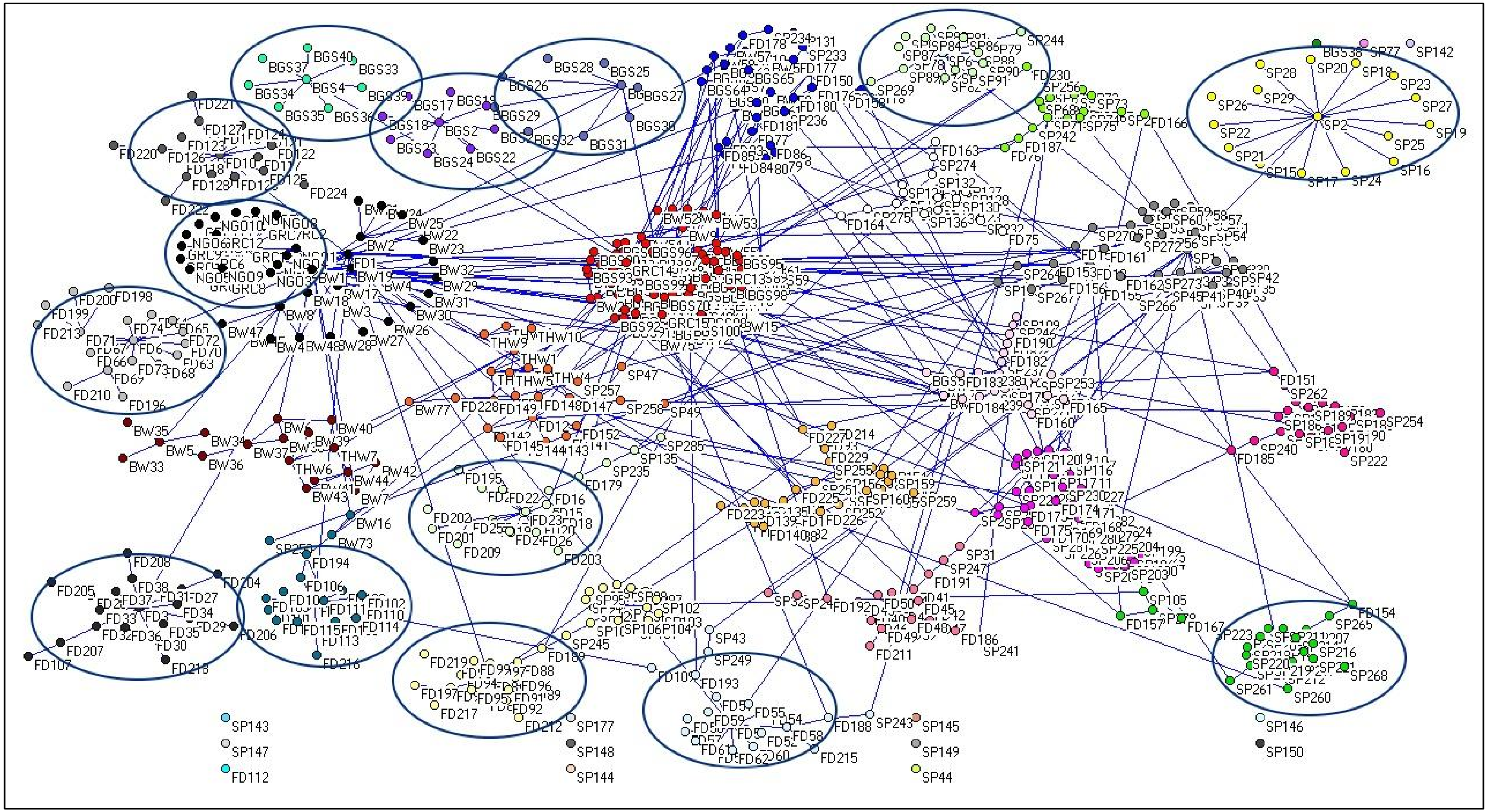


Figure 67. Homogenous coordination-clusters in Elbe Flood response network T1

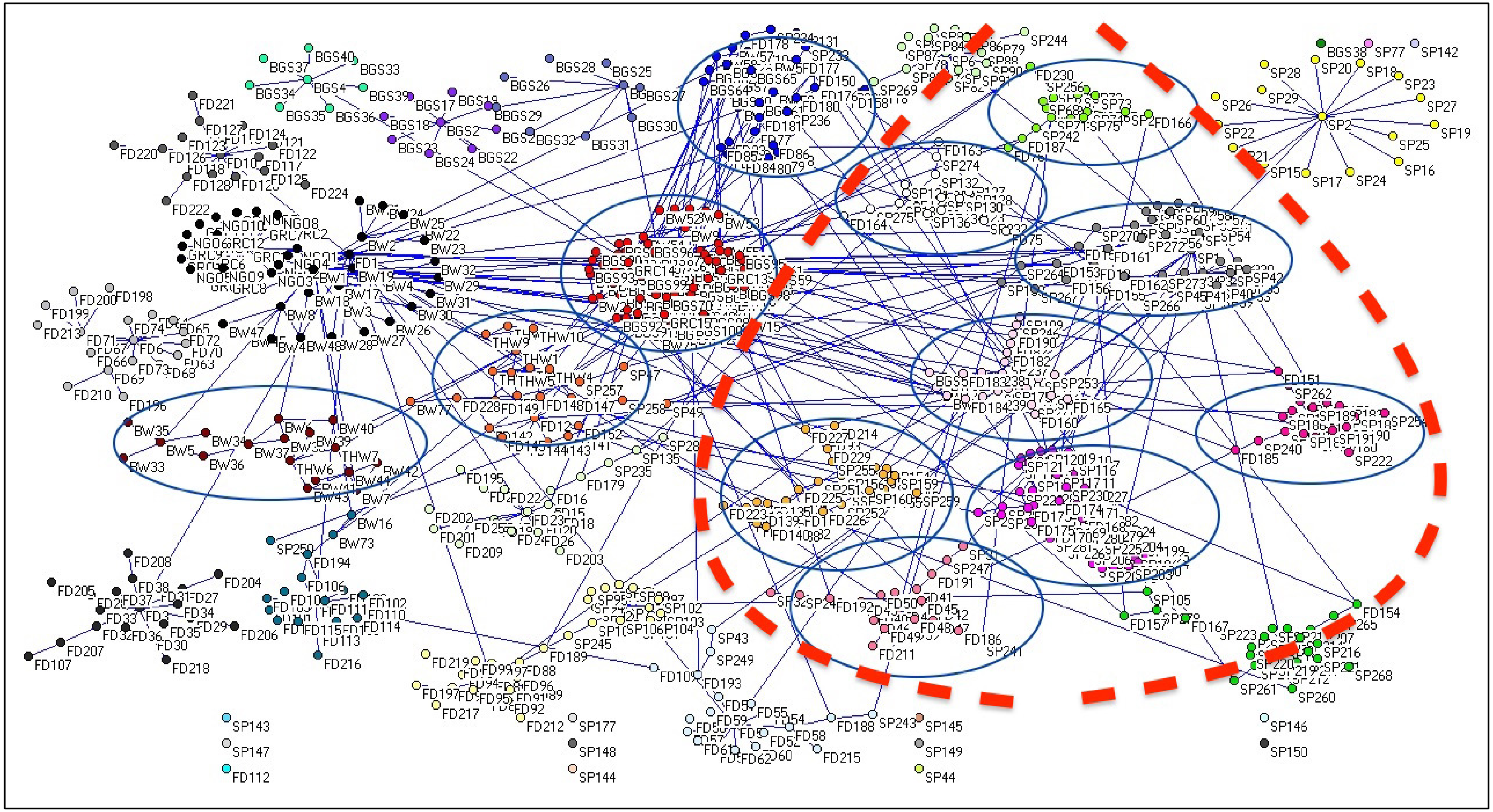


Figure 68. Heterogeneous coordination-clusters in Elbe flood response network T1

5.4 Emerging Leadership in Coordination-Clusters

In addition to applying the clustering methods to the response network, we computed the degree of centrality values to examine the evolution of influential nodes in the coordination-clusters. In Figure 70 and Figure 71, we can see changes in values of nodes' degree of centrality as they switch clusters, which reflect the change in functionality/task carried out by those nodes. Most clusters contained at least one influential node that played a crucial role as information hub to relay information or commands to units from same organization or other organizations in the clusters. The KMar_O is an example where its degree of centrality changed from 1 at T0 to 4 at T1 due to the change of tasks required and engagement of new actors. The same pattern of changes in the degree of centrality value was observed in the Elbe Flood response network as well.

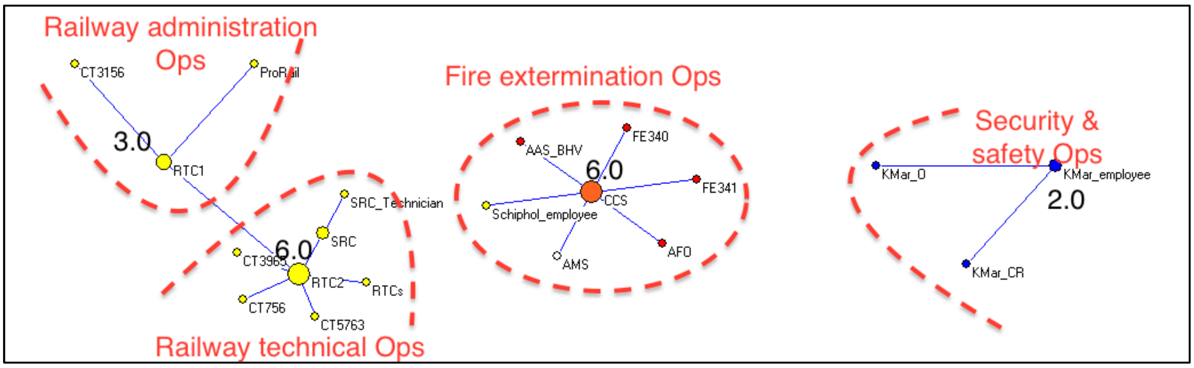


Figure 69. Influential nodes in Schiphol Tunnel Fire response network at T0

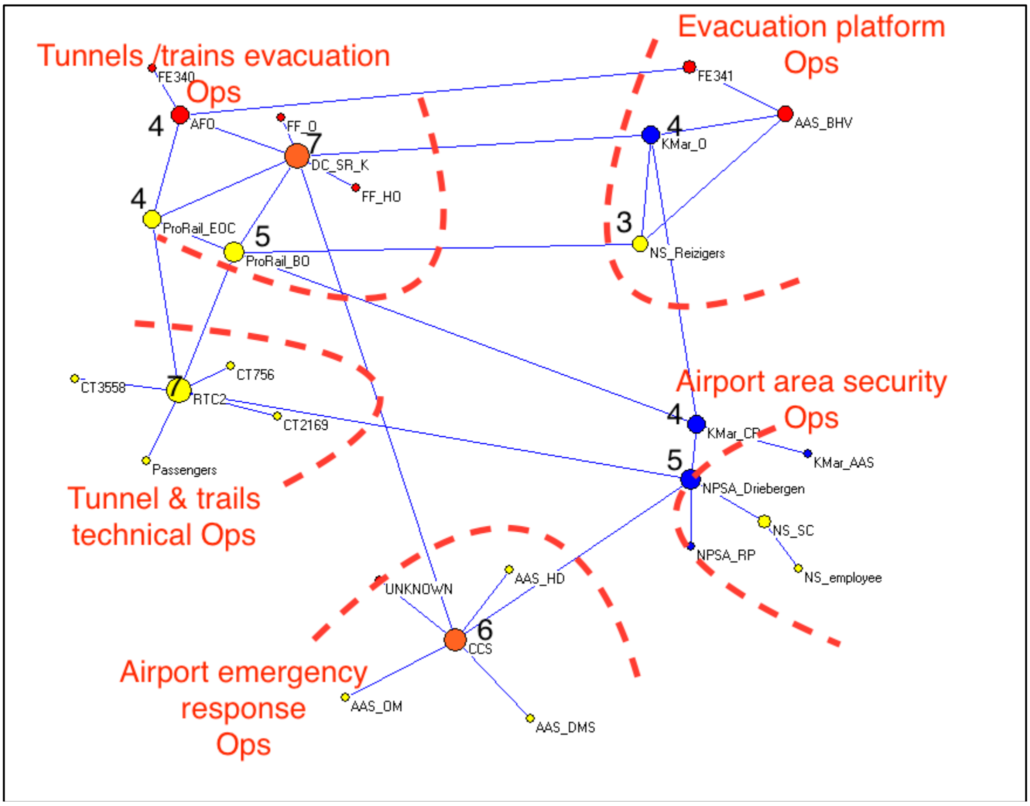


Figure 70. Influential nodes in Schiphol Tunnel Fire response network at T1

5.5 Coordination Flow in Response Operations

In the previous sections we presented results of performing the time-based network analysis of networked-coordination in disaster response operations for both Elbe River Flood and Schiphol Tunnel Fire. However, to complete the analysis of coordination dynamic in disaster response operations, use hierarchical Colored Petri Nets (CPNs) to perform an event-based analysis. As we mentioned before, disaster response operations involve a set of complicated processes that takes place over different authoritarian and jurisdictional levels. The multiple layers of simultaneous coordination actions happening create a very large and complex system to model using classic Petri Nets. The CPNs offered a valuable toolset to visually and mathematically to model the complex systems of disaster response operations. This unique combination of graphical and mathematical representations and a programming language allowed the creation of sophisticated models without having to abstract its relevant aspects. In spite of CPNs' capabilities, for large and complex systems, the CPNs representation becomes less readable and more complicated to trace.

Luckily, hierarchical CPNs offered features, which enabled the representation of large complex systems (Kristensen, Christensen, Jensen, 1998; Jensen, Kristensen, Wells, 2007; van der Aalst, Stahl, Westergaard, 2013). Hierarchical CPN modeling became a great asset to have to model complex systems such as disaster response operations.

The hierarchical CPN model enabled the visualization of processes flow in networked-coordination settings like disaster response operations. The capability of constructing a model describes multi-tiered and network-based complex system provides the ability to test different scenarios and optimize coordination flow to maximize resource utilization and reduce response time. However, scenario testing and process optimization of coordination in response operations was beyond the scope of the current research work.

For both Elbe Flood and Schiphol Fire, the network analysis was a tool to visualize networked coordination in response networks. In a similar way, the hierarchical CPN modeling serve as a translation of the outcomes of the network analysis into a presentation of coordination flow in a network-governed response operation. In the model, functional cluster were translated into sub-processes or modules that can be replicated as needed and encapsulated inside their own authority level in the network. Furthermore, processes such as transitioning between different levels of response (i.e. escalation or de-escalation to/from local, regional or national) were easy to model using hierarchical CPNs. With the modeling we were able to follow resources consumption and actions' execution through the disaster response network. One of the outcomes of the analysis, we can see dependencies of processes like the assessment process which depends on information availability at different levels of response authorities.

In both Elbe Flood and Schiphol Fire response networks, we recognized a bidirectional flow of information (e.g. catastrophe alert, fire alert, situation reports, sensor readings (for water levels or smoke detectors)) and actions (e.g. escalation response levels, force deployment, evacuation) among the different actors in the network (See Figure 71). In addition, the Command and Control nodes were focal points in the network and served as hubs for communicating information and commands. The behaviors of those hubs were translated into conditional statements to govern transition between places in the model.

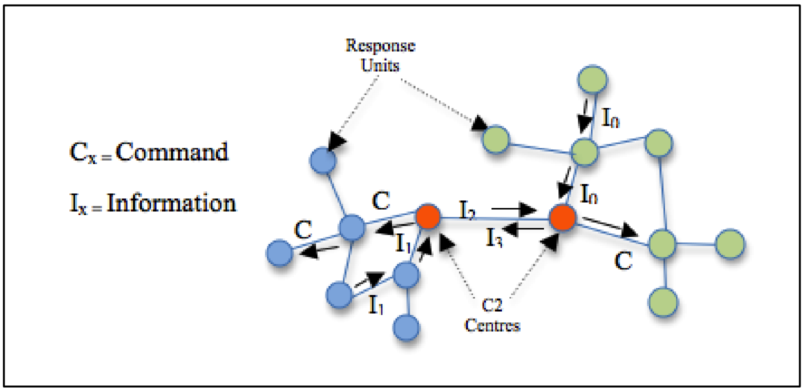


Figure 71. Flow of information and commands in a disaster response network.

The combination of information, actions and resources flowing in the network is a manifestation of coordination dynamics. In order to model dynamic in the response networks subject of this study, data such as exchange information, issue a command (another type of information) or execute a command (action) must me included. The data can be obtained from (1) coordination matrix, (2) heterogeneous and homogeneous cluster, (3) task-based cluster, and (4) hierarchical clusters. In addition, mapping technique used to assign the units and division the response networks enabled us to embed geo-location of the participating units. With such information it was possible to pinpoint authority levels and the administrative jurisdiction of the specific units or divisions. The possibilities of resources availability alert status at the different response levels in crisis management authorities can be described as follows:

1. *Local level*, the information is reported directly by the local authorities to assess the situation.

2. *Regional level*, the information is reported (propagated) from local authorities to the regional level authorities that will trigger the regional assessment process. If resource are UNAVAIL, and EMG Level = LOCAL, then the unavailability will triggers the assessment process for higher level.

3. *National level*, the information is reported directly to the regional authorities to assess the situation. If resource are UNAVAIL, and EMG Level = REGIONAL, then the unavailability will triggers the assessment process for higher level

In Table 24, we show the different options of information about the disaster situation and resources availability in response operations.

Response level	Resource availability	Emergency alert	Decision
LOCAL	AVAIL	ON	NOESCL
LOCAL	AVAIL	OFF	FIN
LOCAL	UNAVAIL	ON	ESCL
LOCAL	UNAVAIL	OFF	FIN
REGIONAL	AVAIL	ON	NOESCL
REGIONAL	AVAIL	OFF	FIN
REGIONAL	UNAVAIL	ON	ESCL
REGIONAL	UNAVAIL	OFF	FIN
NATIONAL	AVAIL	ON	NOESCL
NATIONAL	AVAIL	OFF	FIN
NATIONAL	UNAVAIL	ON	ESCL
NATIONAL	UNAVAIL	OFF	FIN

Table 24. The different possibilities of inputs and outputs for disaster response operations.

In general, the continuation or the escalation of response operations is governed by an assessment process that is carried out by incident commanders or other authorized personnel in the Command Centers. Unfortunately the network analysis fails to capture details of such important part of the response operations. For that reason, using hierarchical CPNs was necessary to present and capture details of procedures execution throughout the duration of disaster response. Another area where CPNs prove to be a great asset is the ability of having different data representations and performing mathematical and logical operations. Therefore, the modeling of decision-making procedures in operations' escalation became possible because of CPN ability to represent the process dependencies such as information availability as tokens and process actions like escalation or de-escalation as transition.

In Figure 72, we show a simple model of an escalation process in response operations based on data form both case studies, Elbe Flood and Schiphol Fire. The model is an abstract of the response operations without including details of underlying tasks (e.g. search and rescue or evacuation, or fire fighting, or enforcing dikes). The model serves as a scaffold for response operations model that can be easily manipulated without having to deal with the complexities the tasks performed. Therefore, the model can be applied to different incidents.

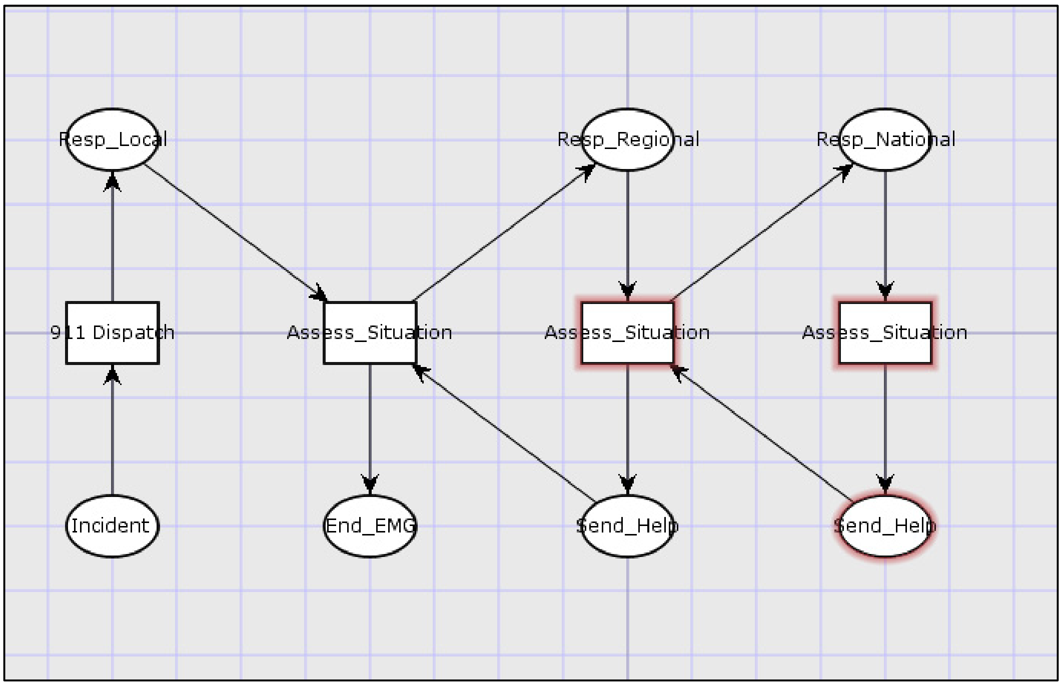


Figure 72. Simple Petri Net Model for response operations.
*Model create using CPNTools 4.0

The construction of a model representing coordination processes in response operations involved decomposing the operations into sub-processes based on tasks performed by the coordination-clusters. We examined the network analysis results of both cases and choose the most common tasks to help constructing the CPN model of the response operations. In this case we choose search and rescue and victims evacuation as it was a common one in both networks. The search and rescue and victims evacuation sub-processes involved actions such as performing search actions, transport victims, registration, provide temporary shelter, and provide food and others. The actions required during those sub-processes were translated into transitions (e.g. Get_Search, Register, Request_Resource). The places in the model represented a stable state in the process such as Camps_Available or Search_Teams. Figure 73 represents a sub-process (or called a sub-page in CPNTools) of the *search and rescue* model using CPNTools. Producing a complete model of a response operations would involve including the rest of the tasks performed the coordination-clusters. With having all the sub-processes modeled, next step is linking each sub-page with its associated level of authority transitions (i.e. local, regional or national). The transitions representing the response levels are shown in Figure 74.

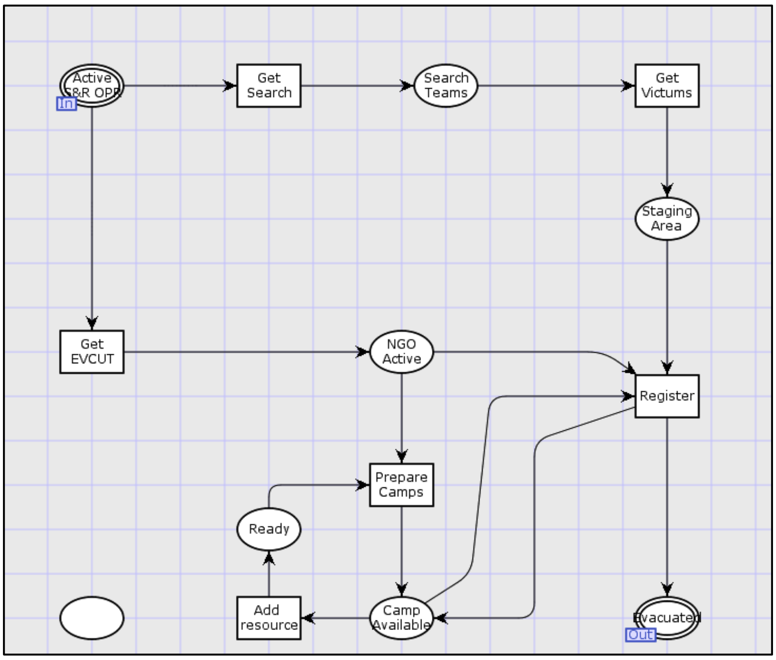
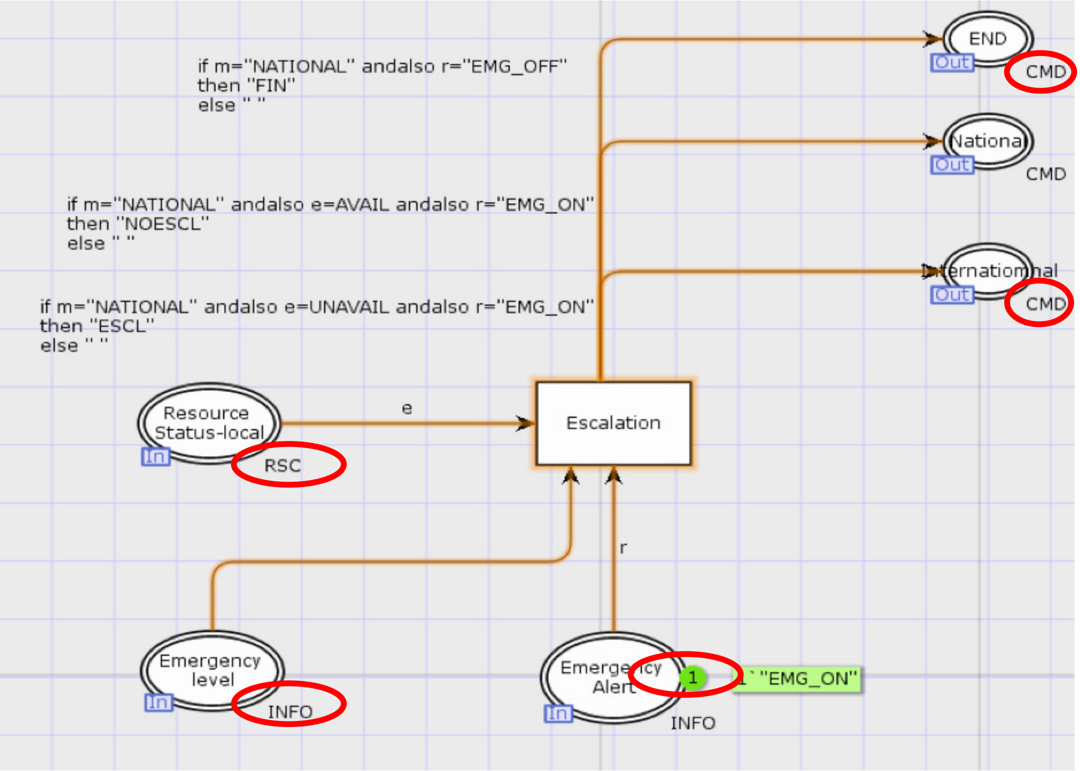


Figure 73. Example of sub-process search and rescue model using CPNTools.

With CPN, the different types of resources consumed within the response network can be represented using COLSET's. A COLSET in CPNTools is an equivalent of data type in programming languages. The COLSET types are declared based on the nature of the resources. For example, COLSET INFO of type *sting* was declared or COLSET CMD of type *string* or COLSET EMG_STAT of type *Boolean* for emergency alert status or COLSET CAR of type *integer*. In Figure 74 illustrates an example of a CPN with different COLSET's are encircled with red. The value of resources or status can be embedded as *tokens* in CPN. In Figure 74, it can be seen that *place* of "Emergency Alert" contain 1 token of INFO with value of "EMG_ON".



```
if m="NATIONAL" andalso r="EMG_OFF"
then "FIN"
else " "
```

```
if m="NATIONAL" andalso e=AVAIL andalso r="EMG_ON"
then "NOESCL"
else " "
```

```
if m="NATIONAL" andalso e=UNAVAIL andalso r="EMG_ON"
then "ESCL"
else " "
```

Figure 74. Example CPN model with different Color Sets defined (i.e. INFO, CMD, and RSC).

As we mentioned earlier, the execution of the different tasks is dependent on having a proper escalation in case of resources unavailability or increase of situation complexity. Figure 76 illustrates a high-level model of coordination flow in disaster response operations. The model was developed based in data from both case studies. It shows the cycle of process flow and the transitions between the different levels. However, the CPN in Figure 76 is only the "Top" layer of the model and transition points such as "Local_Assessment" or "Regional_Resposne" are connected to sub-pages (or sub-processes) that represent models of tasks such as search and rescue or assessment decision-making. For example, Figure 77 shows the Local_Assessment sub-page that represents the model of decision-making process for escalation/de-escalation procedure on the local level.

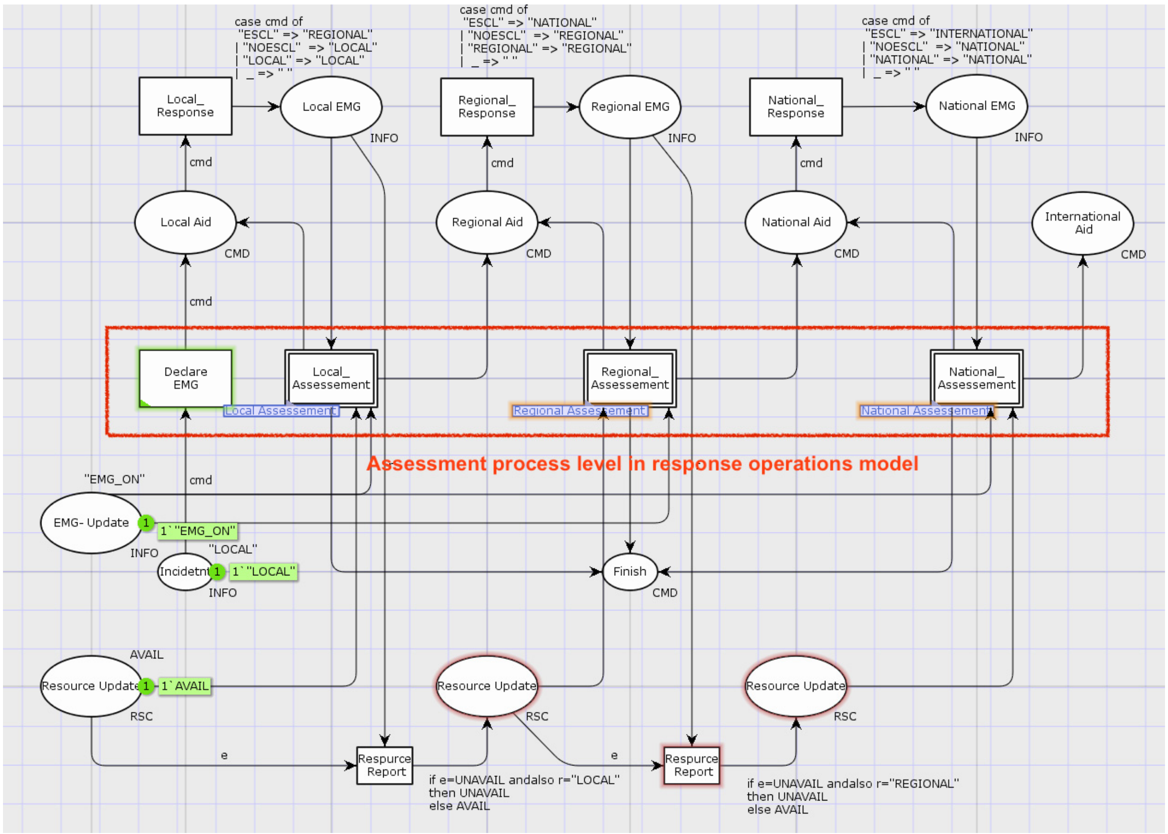


Figure 75. CPN model of the overall disaster response operations.

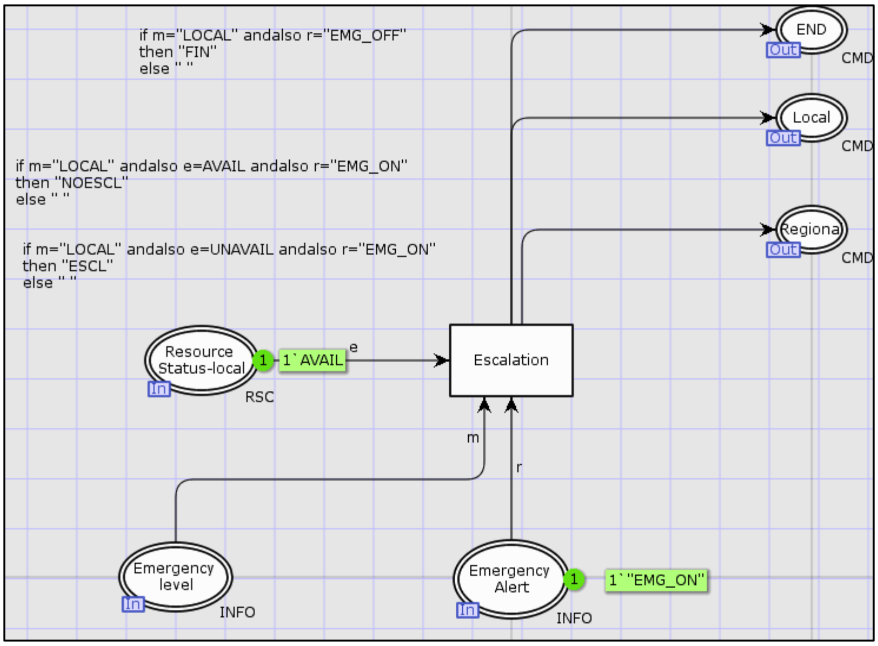


Figure 76. Local assessment process model represented by a CPN sub-page.

As we mentioned that the flow of response processes depends on different sources of information that feed assessment processes over different authoritarian levels (i.e. Local, Regional, National, and International). The model shown in Figure 76 represents a common model for both cases studies, Elbe Flood and Schiphol Fire. The data from table 24 was used to build and validate the common model of the response operations. In Table 24, data from columns: r*esponse level, resource availability and alert status* were used as inputs to the model. At the same time, expected output of the model was validated against data from the *decision* column in Table 24.

In the model shown in Figure 76, we notice that information inputs for each assessment procedure comes from different sources and information regarding alert status or resource availability can take different paths at each level of authority as it propagates through the network. Example of that, the input of Regional_Assessment transition in Figure 76 is a combination of resource availability reported by local response authorities and direct input from the regional levels. The model captures information propagation in the response network within the different authority levels. When we ran the model based on the inputs listed in Table 24, the model didn't produce output as expected several times because of the multiple information sources at each assessment stage or unrealistic input conditions like asking for more resource while the emergency alert is off. Calibration of input values was required as well as modifications to the conditional statements that govern transitions between places. However, the collapse of the model die to multiple information sources helped us to captures another characteristic of disaster response operations, lacking a *common operational picture.* The network analysis could not present such dynamics but it was able to capture the reality of functional clusters formation to cope with disaster conditions when official parties failed to do so.

The use of hierarchical CPN's enabled the construction of a model that integrates sub-processes seamlessly into the multi-layer response operations. Such property provided a flexible modeling canvas for testing different combinations of sub-processes and different scenarios of coordination flows. The model enabled tracing the resource consumption in response networks and monitoring conditional transitions in the operations over a multi-tiered system. Finally, the model can help in improving and trouble-shooting designs of disaster response systems.

5.6 Summary

In this thesis we propose a framework to analyze networked-coordination dynamics in disaster management using a combination of both qualitative and quantitative methodologies. The proposed framework could be an answer the need to a tool capable of providing a dynamic perspective of coordination in network-governed contexts. The steps of the proposed method consists of three stages, (1) a qualitative analysis of incidents using textual analysis and coordination theory, (2) a quantitative analysis using SNA and community detection algorithms, and finally (3) constructing an event-based model using CPN to examine coordination flow in disaster response networks.

The results of applying the methodology demonstrated the method capabilities to analyze complex (or large-scale) and simple (or small-scale) incidents. The ability of controlling the granularity of analyzing coordination-clusters provided a flexibility to examine disaster response networks on different scales (i.e. local vs. global views and team vs. network levels).

Moreover, outcomes of the time-based SNA and community detection algorithm showed consistent patterns in coordination-clusters formation. The patterns can be summarized as follows: (1) response teams or units tend to form coordination-clusters based on required tasks during the disaster events, (2) heterogeneous and homogenous clusters reflect the nature of organizational relationships forming during the response operations (i.e. inter and intra organizational links), (3) emergence of influencing members is affected by the distribution of the coordination-clusters. Needless to say, formation of the coordination-clusters does not particularly follow the official disaster management plans.

The complementary event-based analysis using the hierarchical CPN demonstrated the flexibility of the method to model different scenarios or types of disasters. The disaster response operations were replicated using a two-tier CPN where a high-level (first tier) model that represents the coordination flows in disaster operations within a global context. Where a low-level (second tier) model to represents the different tasks implemented in a disaster response operations from local view. With this we end the results chapter and in the next chapter we shall discuss our findings.