A System Dynamics approach to Critical Infrastructures Interdependency Analysis: the experience of the CRISADMIN Project

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ABSTRACT

Critical Infrastructures are widely perceived as the backbone of today's society and awareness about their security needs is constantly growing. Due to the fact that infrastructures are no longer a public-authority monopoly, investments in security and resilience need to be proven effective and cost-efficient vis-à-vis the emerging challenging and the issues at stake. Decision makers need to assess their investments alternatives by means of scenario modelling tools, such as the CRISADMIN Decision Support System. The CRISADMIN project aim at realizing a DSS based on a system dynamic model of critical infrastructures' interdependencies, able to provide information on the impact of critical events on the infrastructures in object. The paper describe the CRISADMIN applied methodology to model Critical Infrastructures interdependencies, focusing specifically on the energy supply and telecommunication network.

Keywords: Critical Infrastructures, Interdependencies Analysis, Domino Effect, Complex Systems Understanding, Policy Modeling, Systems Thinking, System Dynamics, Computer Simulation

1. INTRODUCTION: THE CRISADMIN PROJECT

In recent years, the awareness about the fundamental role played by critical infrastructures in today's society has spread from limited circles of professional insiders up to decision making level, bringing the issue in the front lines of national and transnational agendas.

The Council Directive 2008/114/EC defined Critical Infrastructures as "an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, […] 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". Reaching consensus around the definition of Critical Infrastructures paved the way for a number of subsequently emerge issues, concerning their management, security requirements, resilience levels and recovery capabilities. Furthermore, as Critical Infrastructures are no longer a public authorities monopoly, growing concern has emerge around the issue of security and resilience related investments. As private actors are driven by cost-opportunity assessments, a twofold objective needs to be pursued. On one side, awareness need to be stimulated among operators concerning the security levels required in light of the criticality of a certain infrastructure. On the other hand, there is a need to understand how to directing and incentivizing effective and efficient security investments.

This latter objective can be broken down in a number of different issues to be addressed, such as:

- in which strategic points should investments be directed in order to maximize their effectiveness?

- which is the expectable long term impact of investments on critical infrastructures security?

- how reaction and recovery timings impacts the cumulative loss of services and the total damages?

Bearing in mind these considerations, the paper presents the CRISADMIN approach for assessing potential socio-economic impacts of critical infrastructures failures in case of critical events. CRISADMIN is a European Commission funded project in the field of Critical Infrastructures Protection (CIPS), which aims at developing a Decision Support System (DSS) based on a system dynamic model of critical infrastructures interdependencies. In order to strengthen the reliability of the CRISADMIN model, four case studies had been set up in order to support the design, to test and to validate the CRISADMIN model. The selected events were the bombing attacks of Madrid 2004; the bombing attacks of and London 2005; the flooding events of 2002 affecting Central-Eastern Europe, Austria, Czech Republic and Germany; and the flooding events of 2007 in the United Kingdom. These events had been selected in light of two main considerations: first of all the likelihood of the terroristic attacks and flooding risk, secondly, the above mentioned events had been chosen in light of their potential impact on critical infrastructures, as both direct target or indirectly as recovery activities supportive systems.

The present paper will be focused on the methodology pursued to realize a system dynamic model of critical infrastructures behaviours, with operative references on the maps and causal loops identified insofar. Before addressing this core part, a number of contextual insights will be proposed to the attention of the reader in order to provide a complete and effective picture of the logical framework of reference of the project activities.

2. A PEEK INTO THE LITERATURE

Critical events not only cause damages to CIs, but due to their relevance in the socio-economic context, have an impact on the entire society. For this reason CIs represent a strategic element for decision makers to be considered while defining first response actions and setting societal policies and investments.

Critical events such as weather extreme events, human errors-related incidents, terroristic attacks were traditionally considered rare events, and emergency procedures were aimed at minimizing aftermaths and accelerating recovery. Such resilience came at a high cost as the wider external environment started to change. In fact, the on-going privatization process of many CIs, changing the focus from a successful service output to the economical well being of the company as a whole, has generated for these assets a "time bomb" effect, by reducing maintenance and delaying replacement programs (Warren & Thurlby, 2012). At the same time, climate changes caused weather patterns to become both more erratic and more extreme, and new threat of terrorism and in particular cyber-terrorism, also emerged, generating a new kind of potentially very high-impact disruption, namely the control-system related damage. Last but not least, as the CIs have become more sophisticated and more complex, their various parts have become more inter-dependent, ultimately increasing the risk of spreading disruptive event effects across different CIs, the so called Domino effect.

In this context, the ability to model socio-economic impacts arising from disruptions to CIs is becoming increasingly important for determining the most effective investment strategies for protective measures and consequence mitigation in case of critical events. While many mitigation measures may appear important and potentially effective, most government agencies need to rank these alternatives to effectively allocate their limited budgets. Furthermore, there is a growing need to understand costs for the entire society - beyond those of the initially impacted infrastructures - to fully comprehend the magnitude of the event and to make the appropriate allocation decisions (Warren & Thurlby (2012).

To date, many powerful simulation tools already exist to understand how networks could be affected physically by major incidents: many of these tools help organizations to improve their readiness to respond to such incidents but part of the problem is less well understood and hardly grasped by these tools. In particular, the relationship between long-term, strategic choices and the ability of infrastructure networks to withstand disruptive events would require further investigation. Whilst it is clear enough that "spending less on assets, systems and people will degrade the system", it is not so obvious how much impact any particular choice will have over long periods of time, neither how choices on different issues will interact.

Crisis management requires numerous resources and tasks from ensuring effective ICTs and transportation networks, the safeguarding of power nets against overload or increasing the number of first responders on the ground. Moreover, each infrastructure, despite its material nature, is embedded in a specific social environment and critical events induce behavioral changes in the people who are part of the system in crisis as well as in the individuals who are involved in the management of the crisis (Orlikowski, 2000). Resilience as a concept can also be divided in a 'material' side (e.g. transportations, energy and communication infrastructures) and human aspects (e.g. capacities of individuals and communities to be self-sufficient, to adapt and to develop psychological toughness). Human behavior during and after crises is often considered chaotic and unpredictable: nevertheless, fostering resilience and responsibility to disasters can enable communities to withstand extreme events with a tolerable level of loss (Mileti, 1999). Stahura, Henthorne, George and Soraghan (2012) demonstrated how being better prepared by having effective strategies to mitigate the crisis situation and the ensuing chaos enhance the resilience of a society. For instance, the lack of trust deserves to be considered as a primary concern, as it can cause individuals to judge certain risks as greater than they are or lose confidence in those leading and developing policy (Rogers, 2007).

Thus, it appear evident that human factors come into play at several levels of crisis management involving individual behavior, inter-organizational coordination, leadership and crisis communication. To understand and model these inputs, a literature review for the CRISADMIN project was focused on human behavior in social systems in the response phase. The review of relevant literature was not limited to a specific type of crisis, based on the assumption that social system variables of crisis responses are generic in their nature, and thus applicable for disparate types of crises – although probably to a different extent. Thanks to the literature review 34 relevant social system variables were identified as well as more general observations relevant to the weighing of social variables in the modeling of critical events. The inclusion of the social variable in the CRISADMIN modeling exercise represent an added value of the work performed as represent a tentative approach to account for a wider range of complexity factors.

3. MODELING INTERDEPENDENCIES BETWEEN CRITICAL INFRASTRUCTURES: A SYSTEM DYNAMICS APPROACH

In the last few years the System Dynamic approach has frequently been used to prevent and manage security/defence issues. SD simulation is capable of inherently taking into account randomness and interdependency, which both characterize the behaviour of real-life business environments. Furthermore, it allows for the inclusion of those “soft” variables typical of the interrelated social systems, which generally are not taken into account in most of the linear modelling techniques still used nowadays. The idea behind the SD-approach is that, if “a system structure defines its behaviour” (Sterman, 2000), then by being accurate in analysing and determining the interrelationships among various part of the system, it would then be possible to define accurately the structure of the problem under study and this would ultimately bring to an accurate understanding of the dynamics of the system. Thus, the SD replicates dynamic business reality with the power to "look into the future" and to understand the impact on multiple key metrics. Additionally, simulation allows the user to capture the specific variability of multiple processes and ultimately provides results, which are orders of magnitude more accurate than deterministic analysis.

Integrating the various aspects retrieved through the theoretical framework, SD simulations have the power to represent the main mutual influences of the various parameters, defining for each influence if it is positive (direct causal relationship) or negative (inverse relationship), thus defining also value and timing of these influences. The holistic approach of SD, on the one side, requires that the entire context is considered and, on the other side, that factors that are perceived as weakly or not related to the processes of interest are not included, in order to not to end up with a model which would then be difficult to manage and/or to interpret. The identification of relevant influences within the system dynamics framework allows for a deep understanding of interdependencies among CIs as well as of possible impacts in case of critical events, by taking into account dynamics of an infrastructure as a function of the operations in the other ones. Such an approach allows for estimating impacts to the socio-economic context represented as a dynamic system without requiring the assumptions of equilibrium solutions. In fact, socio-economic impacts arising from critical events are better described as effects caused by disequilibrium dynamics. So, given the above mentioned features, SD appear to be a feasible and appropriate solution for dealing with issues related to safety and security, and particularly in the area CI Protection.

4. THE CRISADMIN MODEL

Bearing in mind these considerations, a three-steps methodology has been set up and implement in order model complex system's behaviours in critical events, in order to achieve the challenging task endowed by the CRISADMIN project. First of all a theoretical model had been defined, in order to establish the boundaries of the investigation to be performed and to define the data domains, which would have led the subsequent modeling activity. Secondly, a system dynamic model had been designed in order to investigate mutual interdependencies among the systems in object, which can have either reinforcing or dampening effects in case of a critical event occurrence. Finally, based on the work performed insofar, a Decision Support System will be created in order to provide decision makers with a means of testing different investments opportunities at stake, as well as to understand which could be the most effective strategy to pursue in the long run to enhance critical infrastructures' security and resilience.
The preliminary definition of the theoretical framework has had a key role in the process, as it allowed for the definition of the main boundaries and point of reference of the investigation, focusing on the main dependencies impacting on the evolution of the event. Features of the territory and of the socio-economic environment where the critical event occurs, timing of the event (including when it occurs and its duration), preparedness of actors (both as population with experience in similar events and as trained first respondents) were included in this analysis. To this purpose, data domains have been used to group the outstanding parameters to be included in the model. In particular for critical events to be investigated in the CRISADMIN project, the following four data domains have been considered, namely Territory, Events, Environment and Apparatus (Armenia et al., 2013).

Territory included the set of variables and parameters describing the geographic features of the territory, including physiographic factors of the territory including orography (e.g. land profile) and hydrography (e.g. rivers, lakes, etc.; Zanden et al, 2013), and geographical-related factors (like extension or locality), able to have had an impact on critical services or of social aspects (Dao et al, 2013).

Event, referred to the set of variables and parameters defining the "normal life" events with different time frequencies. While the geographical features (of the Territory domain) are independent from time, data related to the Environment and Apparatus domain has to be considered as strongly time-variant. In fact, the modality of certain variables are strongly influenced by time-related conditions, such as working hours, commuting hours, workday, week end, bank holiday and special or season festivities. This dependencies are considered mainly for modeling the evolution of the situation in the very first moments after the critical event occurrence in particular for "weighting" in the instant and in the place of the critical event of the different classes of actors involved, and for defining the full activation of the Apparatus operators.

Environment included the set of variables and parameters related to the presence and the activities of human beings in the territory. In particular for human-made critical events, parameters of the Environment together with those of the Apparatus are very important for a successful response to the crises. Finally, Apparatus referred to the set of variables and parameters related to the professional actors dedicated to the management of catastrophic events and to the recovery of the normal functioning after a disaster.

The main objective of the data domains was to represent with specific parameters, the stage where the critical event happens and where counter-measures should be taken as well as damages assessed. For this reason, social aspects, involved both in the preparedness and in the reaction to critical situations, were included in the Environment and Apparatus Data Domains. In particular, special attention was focused on:

- The actors that participate in the activities being modelled;
- The ordinary events that represent the context's normal life;
- The CIs, in terms of provided services that are focused in the models.

For the purposes of the CRISADMIN project, attention had been focused on three main infrastructures, namely Transport, Energy Supply and Telecommunications. This selection has been based not only on the key role played by these infrastructures within critical events and critical events' management, but also on legislative provisions. In fact, in addition to action on CII protection, within the framework of the European Programme for Critical Infrastructure Protection (EPCIP), the Council Directive on the identification and designation of European Critical Infrastructures and the assessment of the need to improve their protection of December 2008 specifies that "…as such, this Directive concentrates on the energy and transport sectors and should be review with a view to assessing its impact and the need to include other sectors within its scope, inter alia, the information and communication technology (ICT) sector".
Based on the above described methodology, the three infrastructures of reference had been in-depth investigated as to identify and model the underlying interdependencies and causal loops. In the following paragraphs the results achieved in the modelling of the electricity distribution network and in the telecommunication network will be presented.

4.1 Electricity distribution network

The purpose of this sub-model (with reference to the overall CRISADMIN model) is to describe a possibly general electrical energy infrastructure in its 3 fundamental parts: Production, Transport and Distribution. Each part has been modeled according to technical specifications, processes and architecture, taking as a reference the general structure of the Italian Electrical Network. In particular, we had the possibility to interview several experts in this sector who have worked or are still working for some of the main Electrical Energy Suppliers in Italy (TERNA, ENEL, ACEA). Specifically, from the interviews of these subjects, we believe we have gathered sufficient information to describe how such an infrastructure generally works, by identifying the processes, resources and structures involved in the production, transportation, transformation and distribution of electricity (Figure 1).

"INSERT FIGURE 1 HERE"

As it probably happens in almost all electricity networks, energy production facilities produce High-Voltage (HV), which gets transported from the HV-lines on the national primary backbone and from the power plants up to the centers/areas where the electricity needs to be distributed (Figure 2).

"INSERT FIGURE 2 HERE"

Of course, the plants are in some cases outside the Reference Area (or even abroad, if we consider the more general process of the Italian energy acquisition from France or Switzerland, for example) or in some other cases inside the Reference Area (red circle, in Figure 2). The Power plants are thus connected to the primary backbone in HV, which gets carried through the HV-lines to the first transformation sub-network (whose topological structure is generally conceived as a "ring", the black circle in Fig. 2) of the reference area, connecting among them (in HV) the Transformation Cabins, which in turn transform the High Voltage to Medium Voltage (MV). Once the voltage is transformed from such cabins into Medium Voltage (i.e.: in the metropolitan area of Rome, Italy, there are around 70 of these H-to-M cabins), from each H/M cabin, there are some MV lines (yellow lines in Figure 2) departing, with some interconnections among them as backup lines (but generally with a low interconnectedness) on which the cabins dedicated to the transformation from Medium to Low Voltage are positioned. These lines are what we call the second level distribution network, which we will explicitly consider in our model. From each M-to-L (medium to low voltage) cabin, depart the lines supplying the final users (with a center-star configuration). Based on the description of the processes, resources and structures involved, we have tried to develop a causal loop diagram of the infrastructure, as depicted in Figure 3.

"INSERT FIGURE 3 HERE"

As we can see, the production section is divided into energy production plants (*Active Energy Production plants*) and external supply of energy (*External Resources*). So, once produced, the electrical power is transmitted firstly through high-voltage networks, subsequently through medium-voltage networks (with some users of medium-voltage, as for example the Underground Transportation infrastructure) and finally trough low-voltage networks to the final users (which generally include domestic users). This is done in order to minimize "line losses" which would lower the efficiency of the transmission. It's worth mentioning here that line losses are directly proportional to the distance between two links of the transmission network and inversely proportional to the voltage being transmitted. In the model, in order to simulate this relationship, we have considered a percentage of loss (as two parameters, namely: *% High Voltage Distribution Network Energy Loss* and *Distribution Network Perc Medium Voltage Energy Loss*) that depends on the size of the reference area and varies depending on the type of energy, high-voltage energy or medium voltage energy. Furthermore, if the cabins are used to the maximum, due to the joule effect, such percentages of loss tend to increase.

As High voltage energy cannot be physically used from the final users (e.g. in a city), the voltage must be lowered before being distributed, through electrical transformer units (*N° Active Energy Transformation Medium Cabins*) that first transform the high voltage energy into medium voltage energy and subsequently, through other specific cabins (*N° Active Energy Transformation Low Cabin*) into low-voltage Energy.

We have differentiated between Medium and low voltage use because, again as a result of various interviews with users and experts, we have been informed that the Subway system generates a demand for medium voltage energy (*Subway Energy Demand*), while the telecommunication infrastructure generates a demand for energy in low-voltage (*Low Voltage Energy Demand*).

After the H/M transformation process, the medium-voltage energy is distributed inside the reference areas through a distribution network that generally has a “fishnet” configuration. The availability of such MV distribution network (*Medium Voltage Distribution Network Availability*) represents a constraint on the maximum amount of medium voltage energy that can be distributed.
Regarding the electrical energy Demand considered in our model, this is given for the most part by the sum of the Low Voltage energy requested by the Telecommunication Infrastructure, Hospitals and other Emergency Services, and for the rest by the Medium Voltage Energy, mainly influenced by the Subway System energy demand. We will tend to consider the Electrical Energy Demand in our model as relative to an identified Reference Area. In fact, this is determined firstly as a function of the population over the related reference area and secondly as a function of the demand curve that represents the seasonal trend (different hours of the day, different days, different months, etc.).
The simplified diagram reported in Figure 4 describes causal relationships among the various aspects that we have considered in this sub-model and hence shows the most relevant feedback loops that ultimately influence the behavior of the model.

"INSERT FIGURE 4 HERE"

In Figure 4, we have evidenced (bold red arrows) the feedback loop determining the behaviour of the model when the Low Voltage Energy Supply Gap assumes negative values (in other words, when demand is greater than the available energy).

Specifically, when the demand for low voltage energy exceeds its availability, the model tries in a first instance to “push” the transformation capacity of the M/L cabins to their the maximum and/or to activate eventually any idle cabins (they generally represent cabins that were in maintenance and/or broken and can return back as available again, and used as needed) in order to increase the equivalent transformation capacity.

"INSERT FIGURE 5 HERE"

Figure 5 shows the specific behavior described above:

- If the Low Voltage Supply GAP assumes negative values it could means that the Low Voltage Energy demand are increasing;
- In this case you can try to increase the number of N° Active Energy Transformation Low Voltage Cabin;
- The Model, compare the N° Active Energy Transformation Low Voltage Cabin with the Low voltage Energy Demand to obtain (Active Transformation per Low cabin) the Transformation Capacity currently required for each cabins, that is not over the maximum transformation capacity represent by “Low Voltage Cabin Transformation AVG“ (see Figure 6);
  At this moment, a new low voltage Energy demand can be satisfied (in whole or in part), and so the Medium Voltage Energy Demand increases by the variable “Equivalent needs of Low Voltage Energy Demand”. It is important to note that

the demand for medium voltage energy is increased only in case that the Energy Transformation Low cabins can effectively transform energy from medium to low voltage (see Figure 6 where the max transformation capacity of cabins are push to Max how represent with red line) and that the effective increase does not occur instantaneously but with a delay (red arrow marked with two vertical bars that indicates the fact that the cabins are not activated immediately, but to become active need a time).

"INSERT FIGURE 6 HERE"

If such an increase is possible, as said, this means that we need to account for an increase in the demand of low-voltage energy (*Equivalent needs of Low Voltage Energy Demand*), thereby increasing the demand for energy on the medium voltage network (*Total Medium Energy Demand*) that will have to be transformed. This, in turn, increases the quantity of medium-voltage energy to be transformed (*Actual Medium Voltage Energy Production To Be Distributed*), which in turn increases the low-voltage energy that can be distributed (*Max low Voltage energy Production to be Distributed*).

It is also important to note that the Low Voltage Energy Supply GAP can assume positive values (in other words, when demand is smaller than the available energy). In this case the model simulates the same mechanism described above but with a reverse behavior (for example, instead of increasing the transformation capacity of cabins, a servomechanism might act so to reduce the equivalent power effectively transformed from each cabin).

In the following pictures (Figure 7, 8, 9) we have represented the structure of the model that describe when the Medium Energy Supply Gap assumes negative values, which is then the same mechanism implemented for Low Voltage Energy Supply GAP.

"INSERT FIGURES 7, 8 AND 9 HERE"

Regarding the Medium Energy Supply GAP, however, we have also included a mechanism whereby, if the demand for energy increases, the *Active Energy Transformation Medium Cabins* can transform a greater amount of energy, but if the High voltage production plants fail to produce that amount, it is possible to request this additional amount of energy from outside the reference area (Figure 9). This mechanism was suggested by industry experts consulted, which explained that generally each reference area is managed by a "supplier" of energy (i.e.: ACEA, in Rome), and if temporarily the suppliers are unable to produce this amount of High Voltage Energy, it may be required to “ask” for it to another energy “supplier” that is external to the identified reference area (for example ACEA might request this amount to ENEL, another Italian energy provider).

5.2 The Telecommunication network

The telecommunication (TLC) network model starts from the explanation of a telecommunication theoretical process.

"INSERT FIGURE 10 HERE"

Figure 10 represents a typical telecommunication data process from User A to User B. In particular, there are two main types of TLC channels: Mobile and Landline. Regarding the first one, a call starts from the mobile Phone of user A and arrives to the "Base transceiver station" (BTS) through Mobile network, typically radio frequencies. After that, the mobile signal is sent to "TLC exchange" (TLC Centrals), which are linked with the BTS's through landlines. Following some interviews held with Italian telecommunication experts from Sirti S.p.a., there are two main capacity bottlenecks in the system, one affecting the flow of incoming calls in the BTS and the other affecting the flow of calls from BTS to the TLC exchange. Regarding the Landline source, the call starts from a landline Phone (user A) and arrives directly to the TLC exchange, through Landline network. It is worth noticing that TLC exchanges have a limited capacity in terms of the capability of managing and routing calls. Once the calls from mobile and landline sources arrive to the TLC exchange, they get routed to the TLC exchange destination. Upon reaching the TLC Exchange connected to the destination, all data that before had been unpacked, are reassembled and sent to the final user by the TLC exchange nearest to him, either through Mobile or landline channels.
The processes described above, were captured into a Causal Loop Diagram representation. The first part of the CLD, reported in Figure 11 represents the calls flowing through the mobile channel.

"INSERT FIGURE 11 HERE"

"Total Mobile Demand" represents the number of mobile calls generated at each time step over the mobile network. It contributes to build up, over time, the "Mobile active demand", which constitutes the mobile traffic. Incoming mobile calls either get through by finding a free line or get blocked when finding a busy line: in the model, we have represented calls finding the free line if they are able to get through the BTS's, according to a maximum BTS capacity and a "No of active BTS". After getting through the BTS, they get to the "TLC exchange" and either get blocked here (due to insufficient capacity of the central) - "Mobile demand temporary not satisfied" - or get satisfied ("Mobile demand satisfied"). Mobile calls not getting through the BTS, somehow finding the line "busy", according to a "Mobile reattempt rate", can return back in the "Mobile active demand" or definitely abandon, thus flowing into the "Mobile demand not satisfied" state. "Mobile demand satisfied" and "Mobile demand not satisfied", concur to get to define the "Telecommunication Service level" which, in turn, has an influence on the "Mobile Active Demand" in terms of number of "total mobile demand" that can be processed. It means that if "Telecommunication Service level" is low, there is a decrease of "Total mobile demand" that can be processed. The Mobile CLD reveals 5 main feedback loops (Figure 12, 13, 14, 15 and 16).

"INSERT FIGURES 12, 13, 14, 15 AND 16 HERE"

In the "Mobile Traffic infrastructure" CLD there are 5 feedback loops. Figure 12 (Feedback Loop 1, reinforcing) describes the lifecycle of a successful call. Once a call makes it through the two constraints check in terms of resources of the telecommunication network (thus, BTS and Centrals), it basically reaches its destination ("Mobile satisfied demand"). "Mobile satisfied demand" increases "Telecommunication service level" that, in turn, has a positive effect on the perception that people have on the telecommunication service, thus increasing (over time) the "Mobile active demand" in terms of number of calls ("total mobile demand") that can be processed. On the other hand, if "Telecommunication Service level" is low, there is a decrease of "Total mobile demand" that can be processed.
Figure 13 (Feedback Loop 2 - reinforcing), describes the dynamics of reattempting a call, which cannot be processed due to a constraint on the BTS maximum capacity, thus passes into "Mobile demand temporary not satisfied" and hence, can return into the "mobile active demand" level given a certain "mobile reattempt rate".
On the other hand, in Figure 14 (Feedback Loop 3 - balancing), if a user could not reach a free line after some call attempts, this call would be not satisfied, thus conceptually flowing into the "mobile not satisfied demand" state, decreasing the "Telecommunication service level" that in turn, and over time decreases the request for such service.
Figure 15 (Feedback Loop 4 – reinforcing) represents the lifecycle of call that arrives to the central after getting through the BTS, and either gets through (thus, under our assumptions, ultimately reaching its destination) or gets blocked due to a capacity issue in the Central. When the call gets blocked, due to this, it could return into "mobile active demand" through the "mobile reattempt rate". On the other hand, in Figure 16 (Feedback Loop 5 - balancing), if a user could not reach a free line after some call attempts, his call passes into the "mobile not satisfied demand" state, thus decreasing the "Telecommunication service level" that in turn, and over time decreases the request for such service. The overall TLC CLD is represented in Figure 17.

"INSERT FIGURE 17 HERE"

5.3 The Transportation Sector

In this section we will describe the main features of the Transport Infrastructures, as it is being modelled at the moment.

We will consider the Transport Infrastructure as composed of three main distinct sub-modules, and namely:

1. The Subway System
2. The Other Means of (Public) Transport System
3. The Private Transport System

Subway System:
The assumptions behind the model of the Subway System rely on a situation very similar to what is depicted in Figure 18.

"INSERT FIGURE 18 HERE"

We consider a structure of subway lines that are not "physically" interconnected (that is, there are no railways exchanges or junctions) but that are connected at the "passenger commutation" level. We won't consider at this level the "deposit" stations (which means points on the line where trains are stored, mainly during the night) and just consider the presence of **Stops** (where passengers basically enter or exit the Subway Systems) and **Stations** (where passengers can also commute between lines).

"INSERT FIGURE 19 HERE"

A Stop (or Station) also has the characteristic of separating two consecutive trunks of a line (as shown in Figure 19)
The various main elements of the System thus are:

1. people demanding for a service (subway demand)
2. a network of a certain number of lines (no. of lines), each composed of several trunks (avg. no. of trunks per line)
3. an amount of stops and stations per line, each capable of accepting (on the platform side) a maximum number of passengers waiting for a train
4. a certain number of trains per line, each capable of transporting a maximum amount of passengers

Among the additional assumptions that we did to simplify the problem are the following:

a. each passenger takes a trip that has an average duration
b. we do not consider the availability of idle trains (trains ready to get into the network to support an increase in demand)
c. we do not consider any standard maintenance of trunks/lines or stations
d. if a trunk gets broken, it blocks the whole Line until it gets repaired. If a stop gets broken, it just diminishes the ability of demand to access the subway system (the overall platforms capacity decreases)
e. we do not consider any maintenance of trains, as these dynamics do not impact in a decisive manner on the system, especially in the considered time windows for our simulations
f. if a train gets broken or damaged, it also has the potential of blocking the whole line (for the intrinsic characteristics of the subway – and in particular, some of the main Italian subways), thus deactivating all active trains on a line (without distinguishing the direction of march)

Under these assumptions, we can consider that the overall subway demand gets served under several constraints:

- that there is enough space on the platform (given a certain capacity of stops and stations), otherwise they cannot physically enter the station and may decide to leave, eventually for other means of transport

- that a train arrives in a station/stop
- that there is enough room on the trains to get on board otherwise they cannot physically enter the train and may decide to leave, eventually for other means of transport
- once aboard the train, they spend some time (average duration of travel) on it and after that they get off the train and are assumed to have reached their final destination

After describing the assumptions and constraints that we have identified in our scenario, we can thus describe the main processes that we will consider when modelling the Subway System:

- **The Voyage flow**: people entering a station or stop, queuing for the subway service, get served (get on board, constrained to the maximum capacity of trains in service), and release the resource (get off the train and arrives at destination)
- **The Stations/Stops flow**: a station/stop can be either Active or Inactive. If Inactive, this means that:
  - There are lesser destinations (stops) and the avg. duration of trip increases
  - There is less platform capacity (thus more people leave to Other Means of Transport)
- **The Lines flow**: a line can be either Active or Inactive. If Inactive, this means that:
  - There are lesser destinations (the avg. number of stops per line) and the avg. duration of trip increases
  - There is less platform capacity (thus more people leave to Other Means of Transport)
  - There are lesser trains in service
- **The Trains flow**: this describes the fact that trains can find themselves in one of the following three possible states:
  - In transit: this means that they are actually moving on a trunk between two stations/stops;
  - In Station/Stop: after an average duration of the trip among two stations (which roughly speaking also represents the avg. waiting time of people on the platform), train arrive at stations and release passengers
  - Broken: this, as said, has the potential to block the whole line, which means:
    - Fewer active stations/stops (as a whole line is blocked) and thus fewer embarking capacity
    - Fewer active trains (as a whole line is blocked)
    - More people abandon to Other means of Transport

The following picture (Figure 20) describes these macro processes in terms of Stocks & Flows.

"INSERT FIGURE 20 HERE"

We will also have to consider the calculation of a Service Level for the Subway Transport Service and a matching of such a service level with transport alternatives (Other Means of Transport and/or Private Traffic), thus describing how people decide (when the Subway SL goes below a certain threshold value) to move to an alternative transportation method (function of the SL and Traffic KPIs from the other two subsystems)

Other Means of Transport System:
In this case the situation simplifies quite a bit. In fact we do not have a real restriction in terms of available space to manoeuver as in the case of the Subway: there is no real space to manoeuver underground, unless properly designed, but very few subway systems – only the largest – have these spots and there are in general very little margins to set broken trains on one dead-end or dead trunk and continue with normal service. This constraint is not present when “over” ground and not constrained to railways. Under these assumptions, the OMT section mainly refers (in our model) to the Bus Transport Network.
Among the assumptions that we will introduce for this Sub-System:

- we will not consider any “platform” constraint (people can queue indefinitely along the road!)
- The maximum OMT Transport Capacity (in terms of passengers) is given by the *Number of Active Buses * Max No. of Passengers x Bus*
-
- We will assume that Buses can get broken and go to maintenance without blocking the whole “line” they belong to, since there will be some idle buses (at deposits) ready (almost) to become active in substitution.

This gives birth to a structure very similar to the one of the Subway System in the main process of people queuing to get aboard, stay on the bus (In Transit) for a certain avg. trip duration and then get off and arrive at destination. The lifecycle of active buses is described by the related stocks & flows co-flow telling us that buses can either be Active (At the Stop and In Transit), or non active (Idle and Under Maintenance).
The following Figure 21 shows the related SFD depicting the process just described.

"INSERT FIGURE 21 HERE"

Also in this case, we will have to consider the calculation of a Service Level for the OMT Service and a matching of such a service level with transport alternatives (Subway and/or Private Traffic), thus describing how people decide (when the OMT SL goes below a certain threshold value) to move to an alternative transportation method (function of the SL and Traffic KPIs from the other two subsystems)

Private Transport System
This subsystem is basically conceived to constitute an alternative to the Subway and/or the OMT, and refers to (private) vehicles circulating in the area. It includes an evaluation of a parameter related to the Traffic in the area, which however necessarily includes all vehicles on the surface, which means Private Vehicles plus Buses (in our case).
The base model is a simplified version of the OMT one, as described in the following picture (Figure 22):

"INSERT FIGURE 22 HERE"

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5. FURTHER DEVELOPMENTS & FUTURE WORK

Decision makers need to understand the consequences of policy and investment options before they enact solutions, particularly due to the highly complex alternatives available for protecting the nation's CIs in today's threat environment. An effective way to examine trade-offs between the benefits of risk reduction and the costs of protective action is to utilize a decision support system that incorporates threat information and disruption consequences in quantitative analyses through advanced modelling and simulation. The proposed System Dynamic approach can provide decision makers with a useful means to understand and evaluate some of the expectable risks triggering CIs. The CRISADMIN approach can be easily used in contexts where standard analysis is made difficult by the wide range of available data and/or relationships in place. In particular, it would be specifically helpful in those systems highly influenced by "soft" variables, connected to human behaviour. Insofar, the CRISADMIN project activities have outlined the main features of the CI's contextual framework and have mapped the causal relations between the identified parameters of reference.

The systemic approach, which closely follows the Systems Thinking & System Dynamics Methodology prescriptions, has allowed for a simple yet very effective representation of such context, with a preliminary identification of those parameters that, in a "domino effect", influence the behaviour of the whole interconnected system. The sub-systems described in Chapter 4, relevant to the sample context, constitute just the starting phase of the modelling process and have been qualitatively modelled, at the present stage, in their "business as usual" functioning. Once the entire context will be integrated into a quantitative model, with interdependencies between CIs being explicitly modelled and with aspects belonging to each Data Domain (including the "social" cross domain) being reasonably accounted for, the direct impacts of critical events on one or more of the sub-systems will be introduced. According to the type of event selected, the most concerned variable of each subsystems will be appropriately stressed and the model will produce the various scenarios to be analysed.

The next step in the Project will be the design and development a CRISADMIN Decision Support System prototype, which will allow for the execution of simulation runs and comparison of the effects on the territory. This will enable operators, both territory analysts and first responders, to analyse the impacts of different situations, in terms of nature and size of the event, timing and extent of direct damages, as well as to comparatively assess different possible evolution in presence of alternative mitigation policies and/or different resources deployment.

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Annex 1 – Referenced figures

Figure 1: Electrical Energy Infrastructure – overall production-to-distribution process

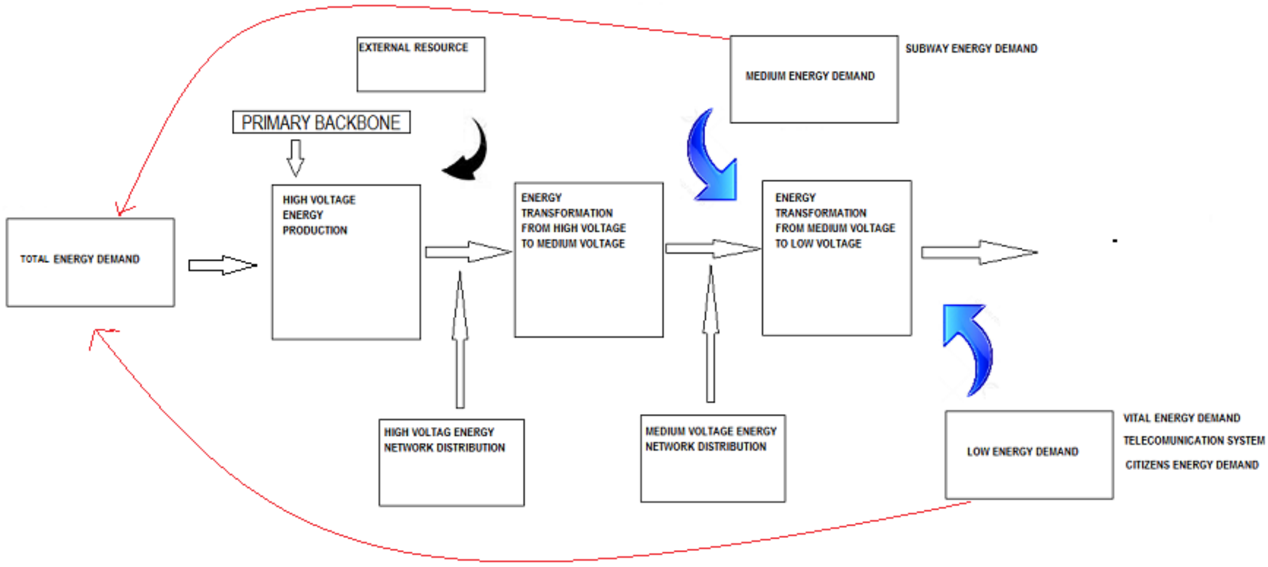

Figure 2: Electrical Energy Infrastructure – general architecture

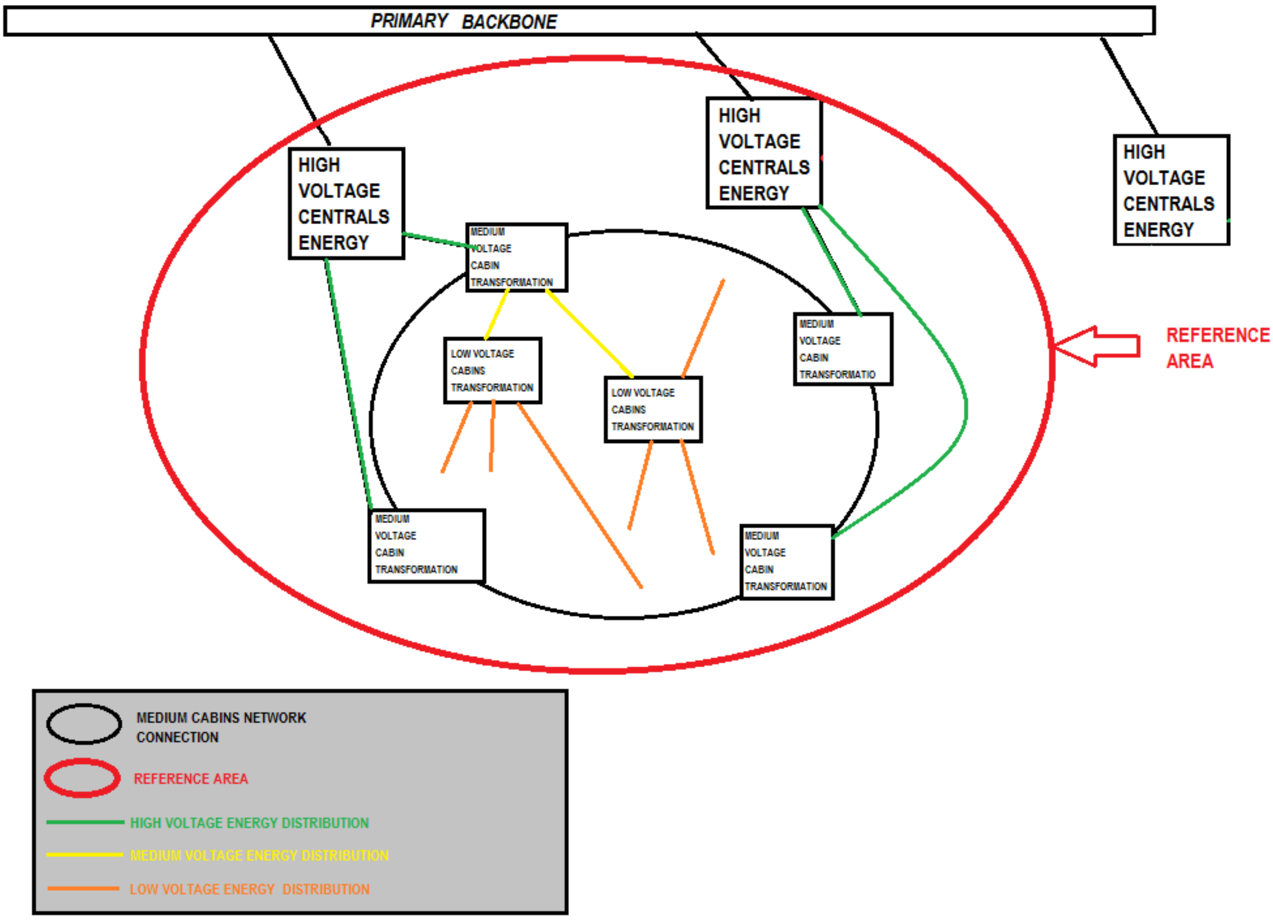

Figure 3: CLD of the Electrical Energy Infrastructures

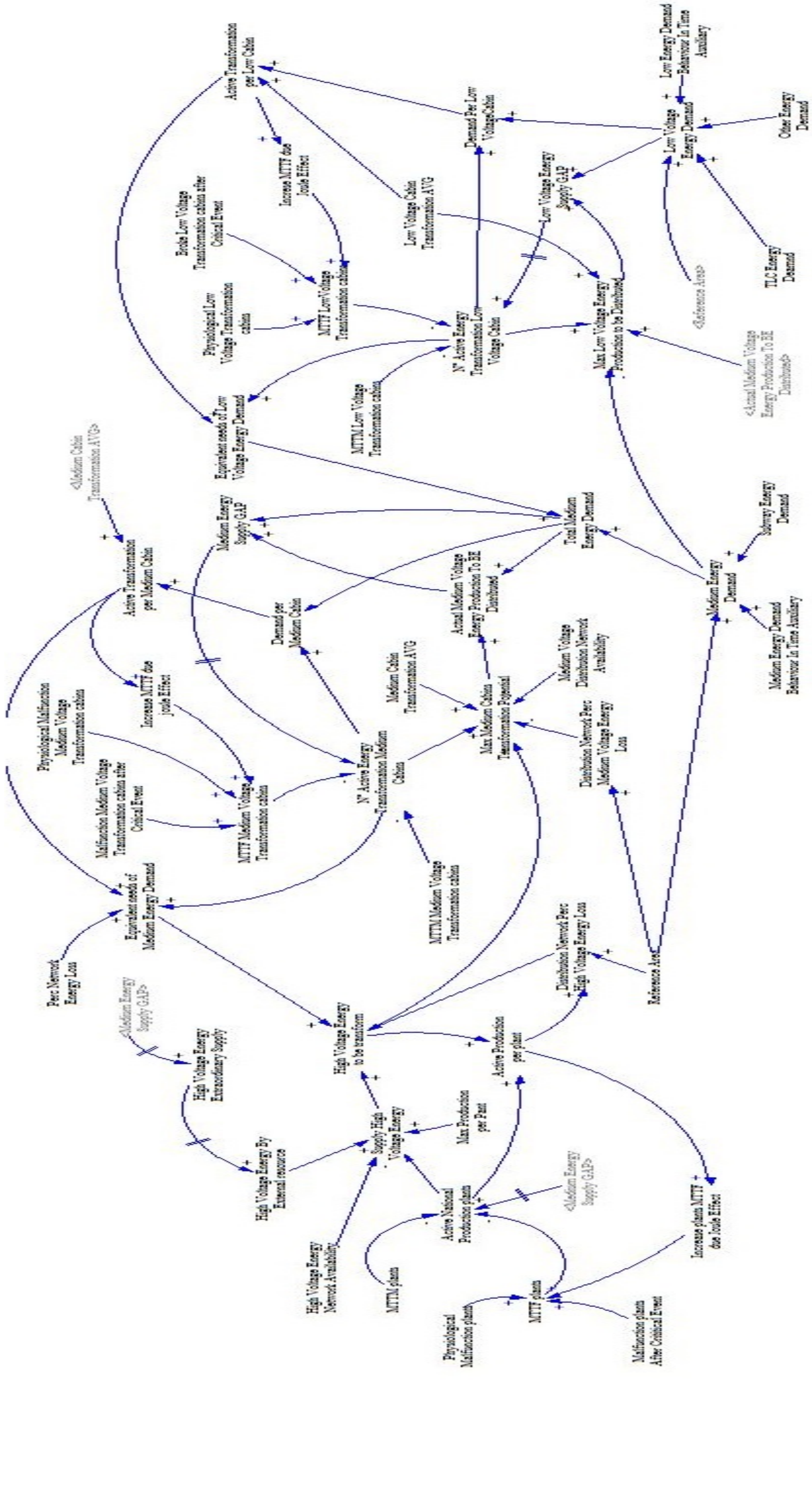

Figure 4: Electricity CLD Simplified – Explanation of first causal loop regarding Low Voltage Energy Supply GAP

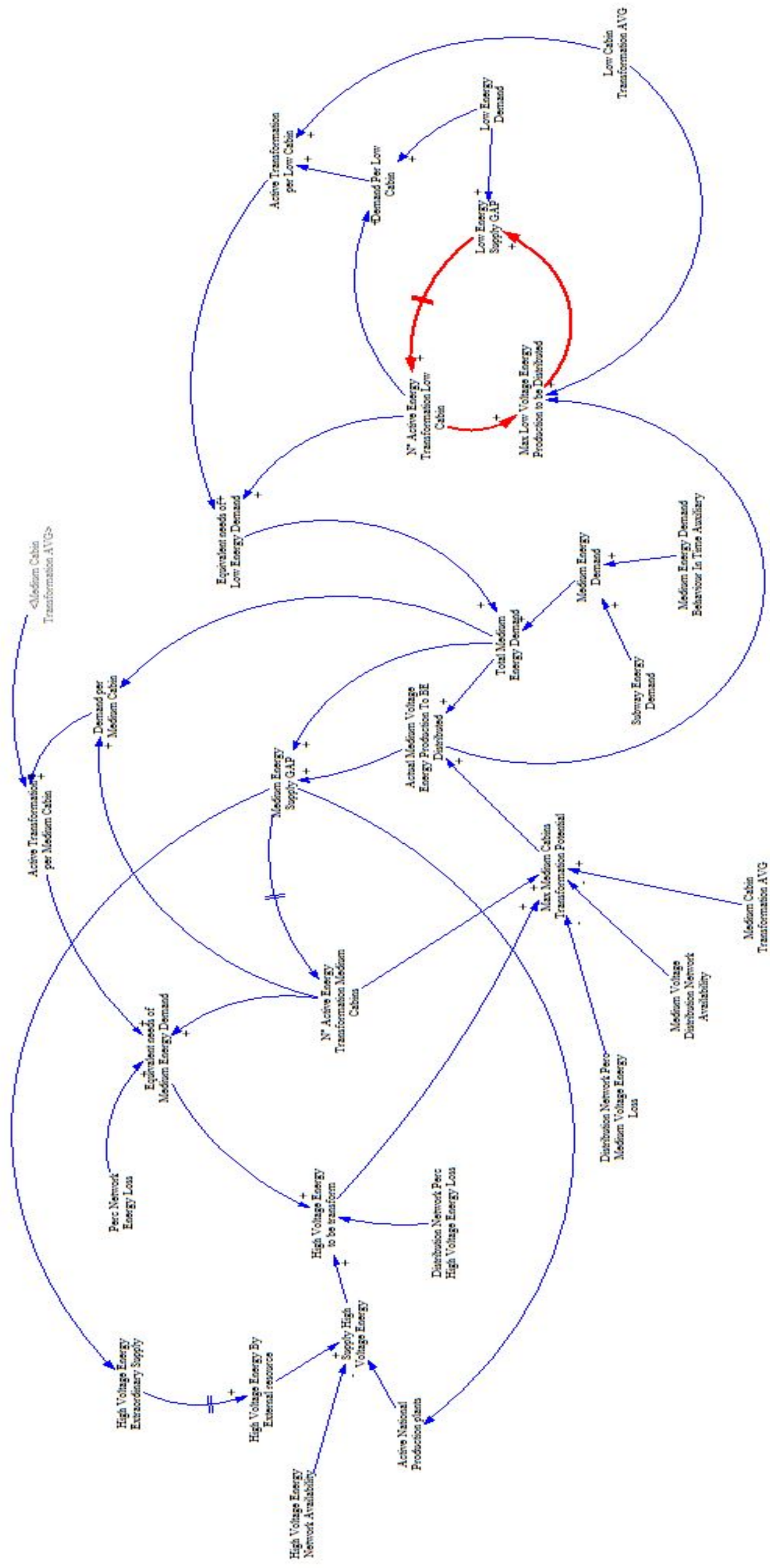

Figure 5: Behavior Explanation of increase Low Voltage Cabins transformation capacity

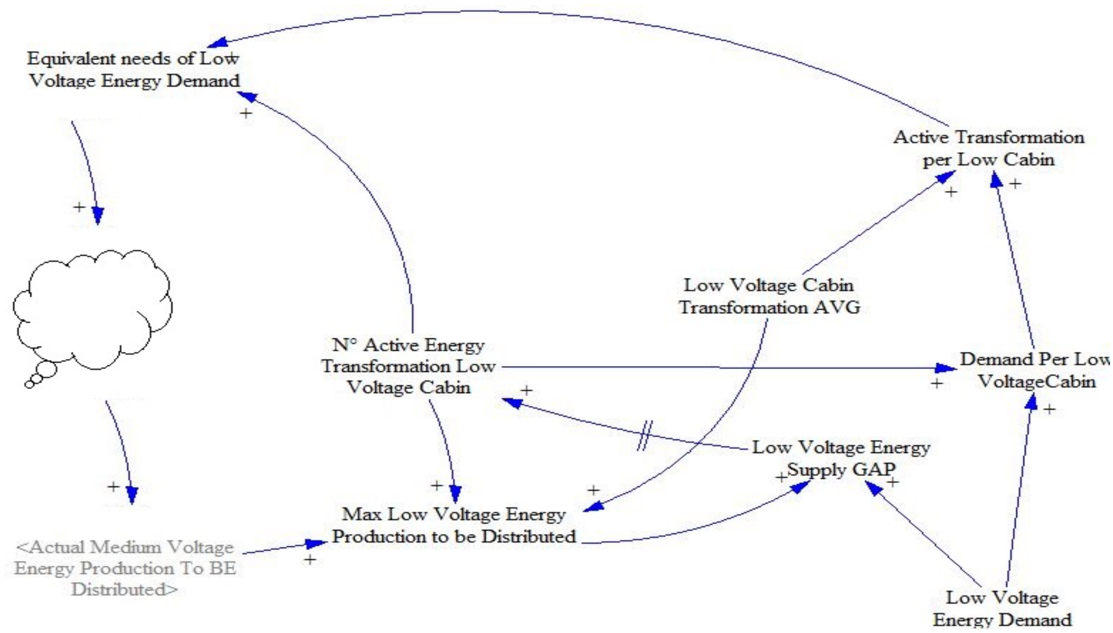

Figure 6: Graphical representation of Low Voltage cabin transformation AVG

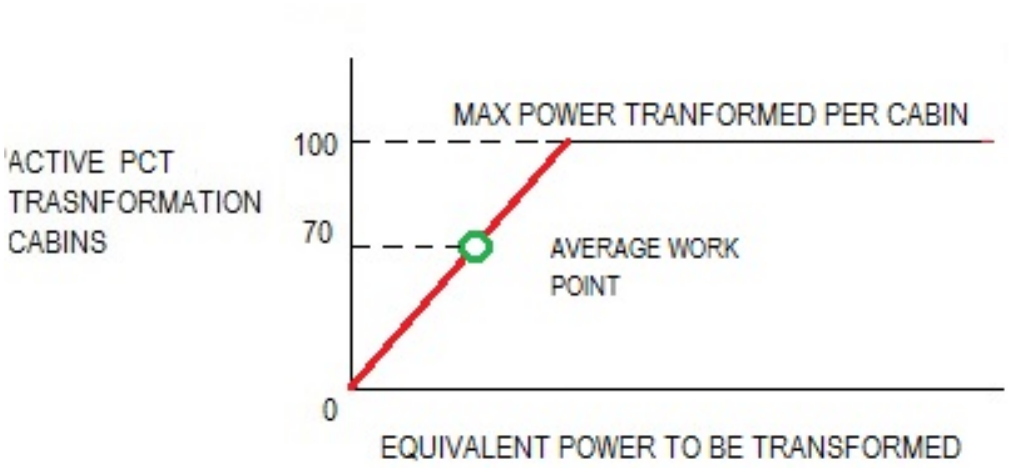

Figure 7: Second causal loop regarding Medium Voltage Energy

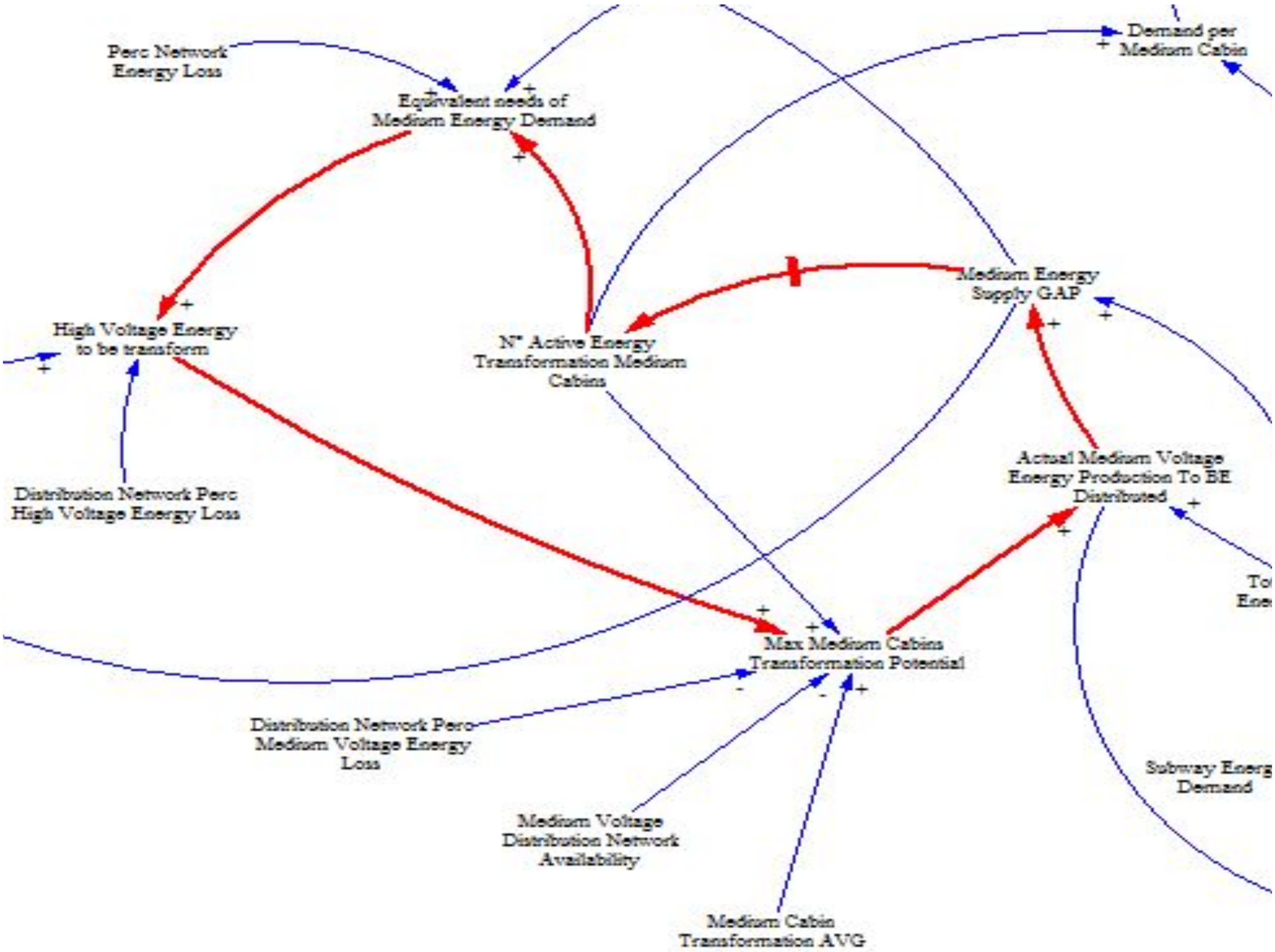

Figure 8: Third causal loop regarding Medium Voltage Energy Supply GAP

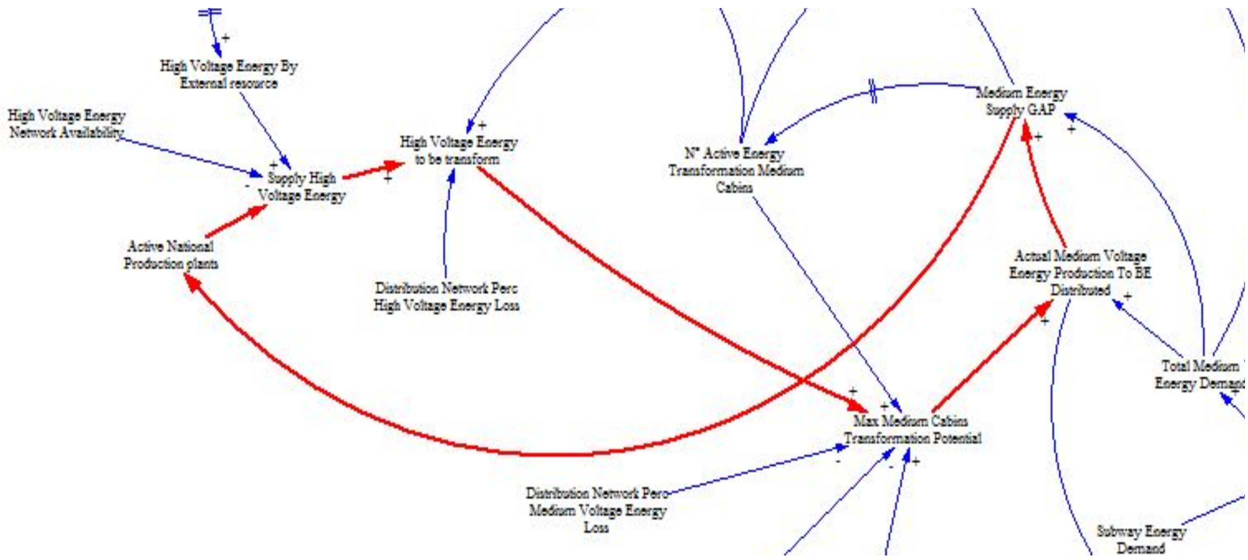

Figure 9: Fourth causal loop regarding Medium Voltage Energy Supply GAP

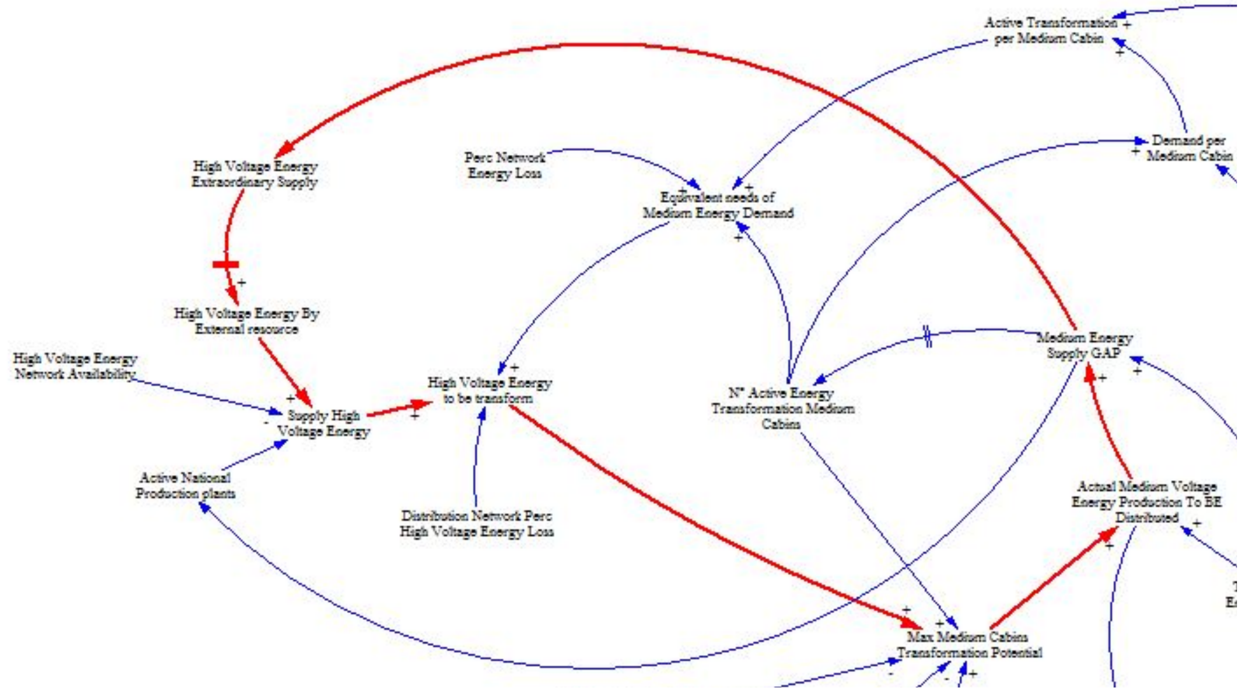

Figure 10: The Telecommunication network: our theoretical frame

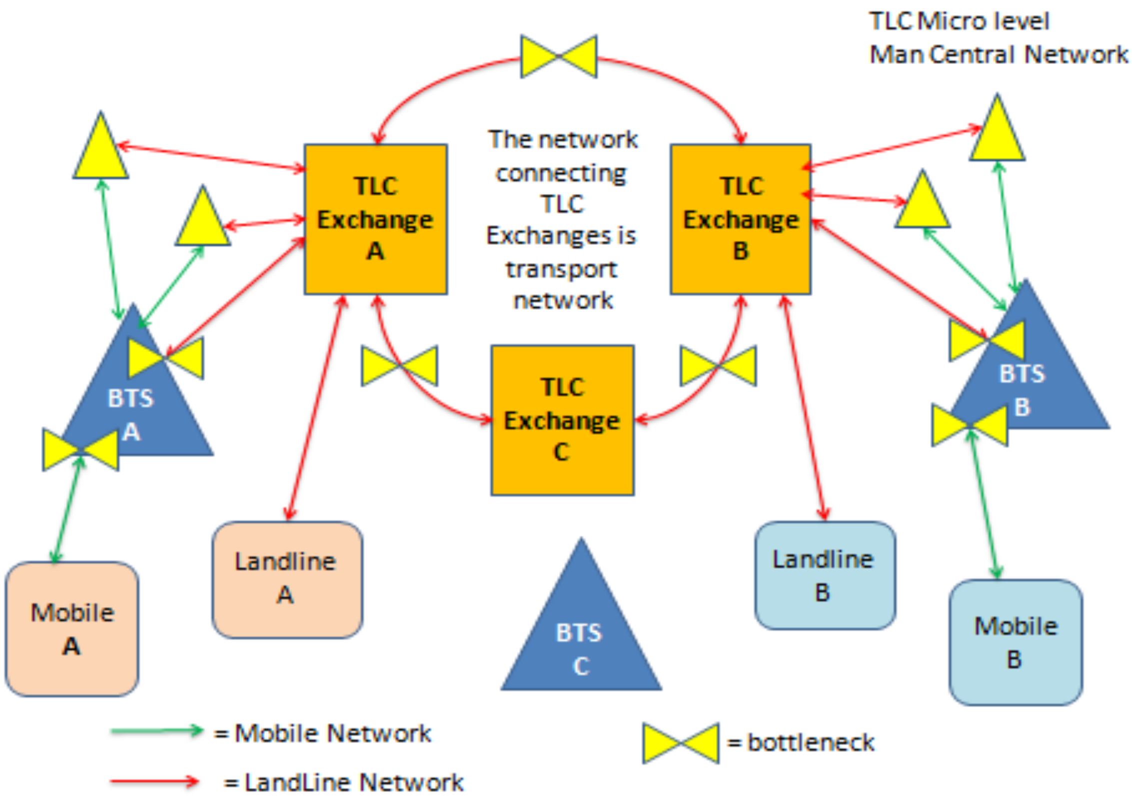

Figure 11: CLD Mobile Traffic Infrastructure

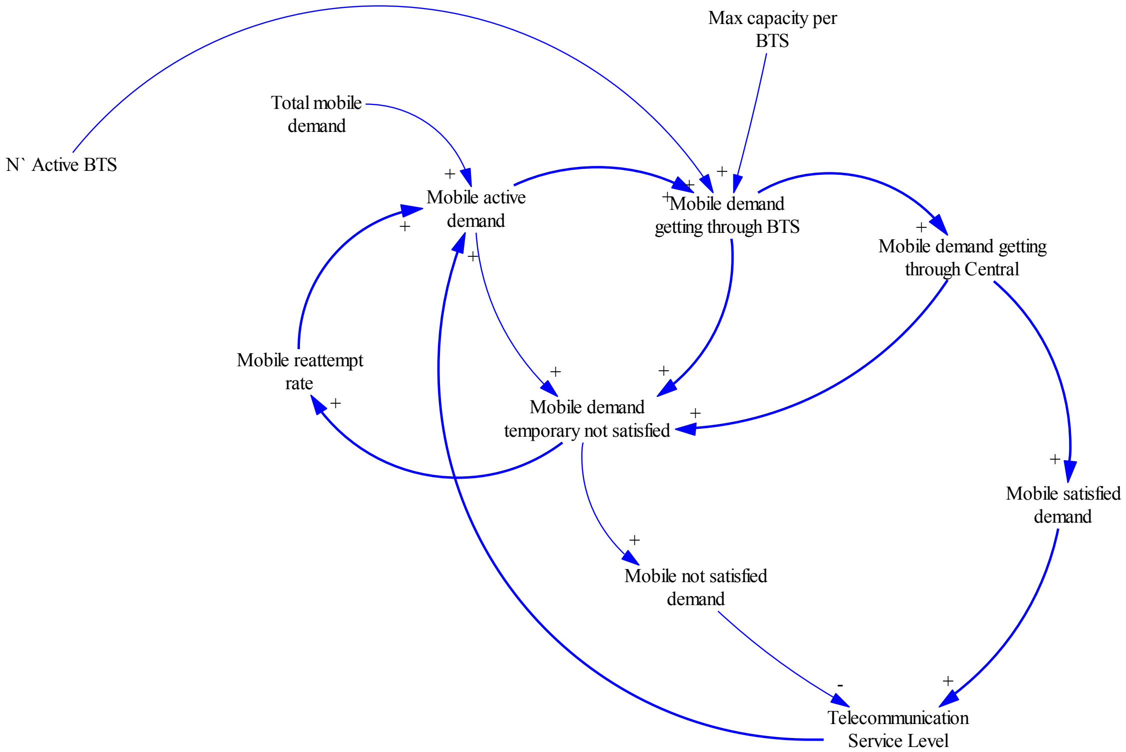

Figure 12: Mobile Satisfied Demand

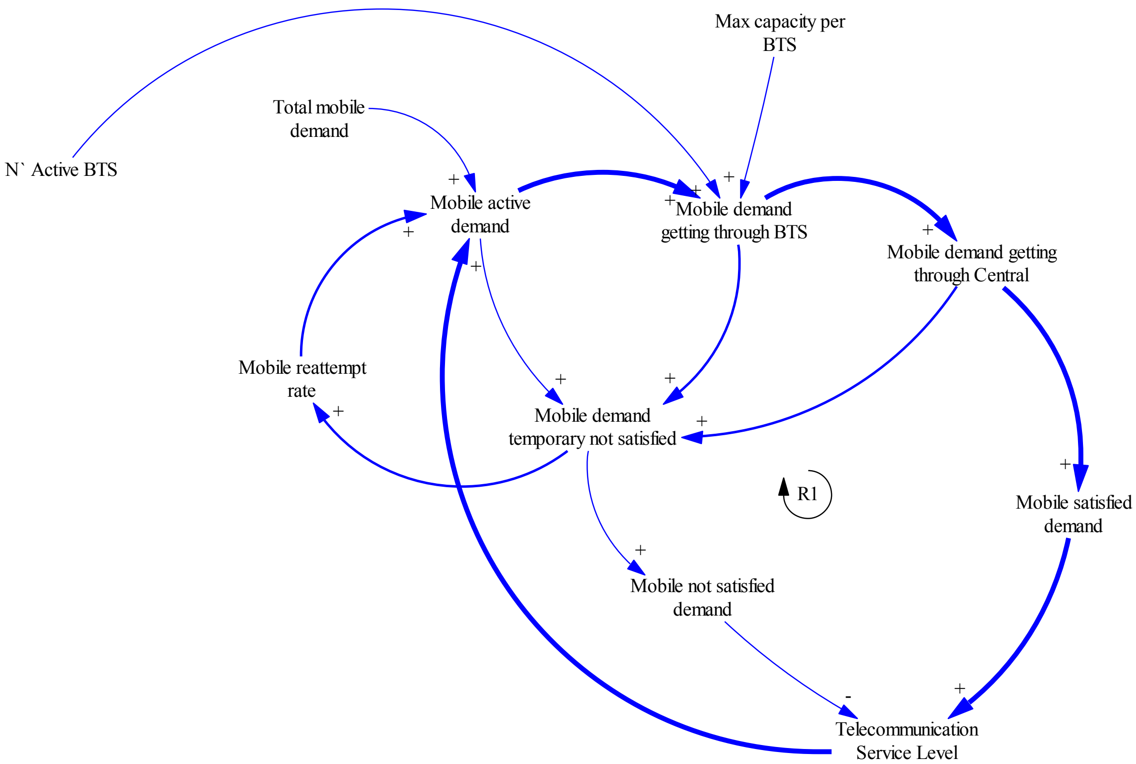

Figure 13: BTS' Bottleneck

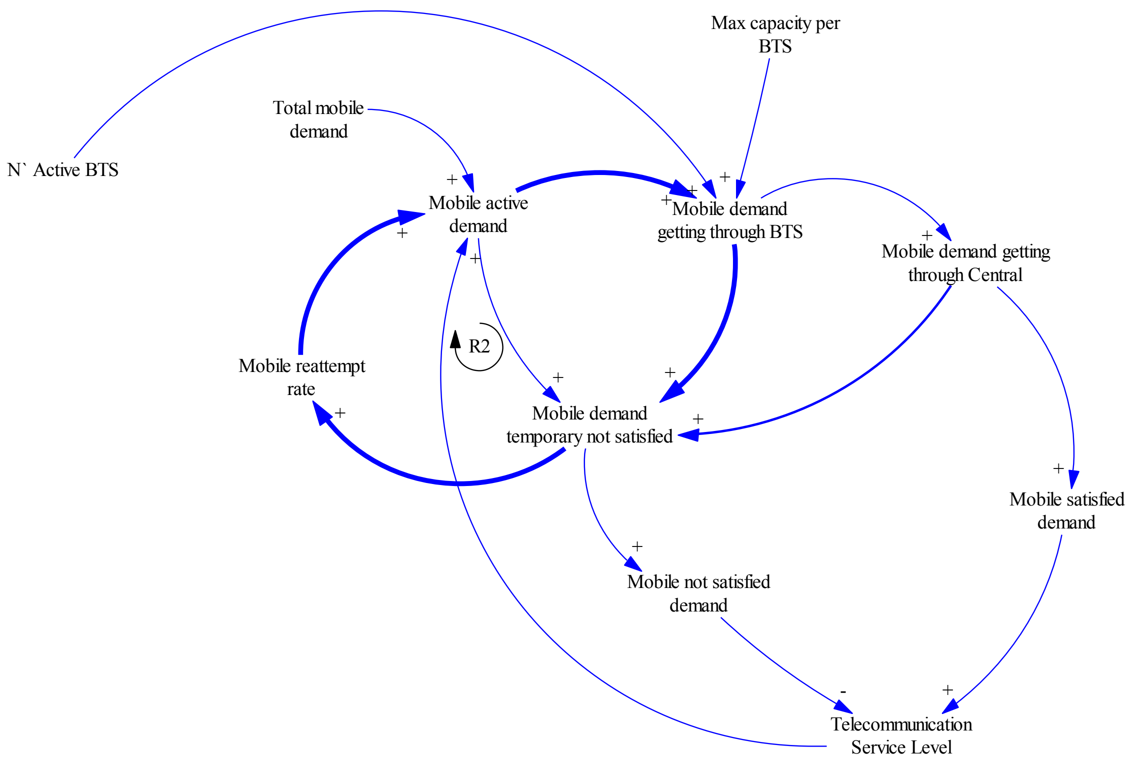

Figure 14: Mobile Demand Not Satisfied

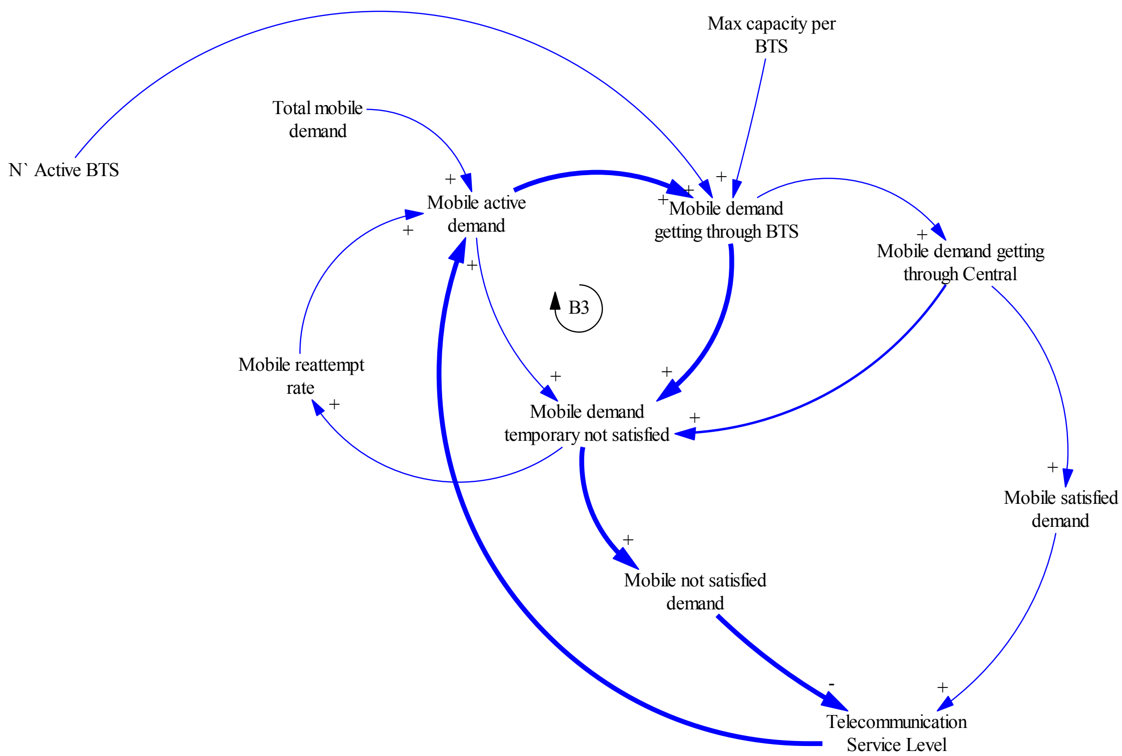

Figure 15: Centrals' Bottleneck and Mobile Recall Rate

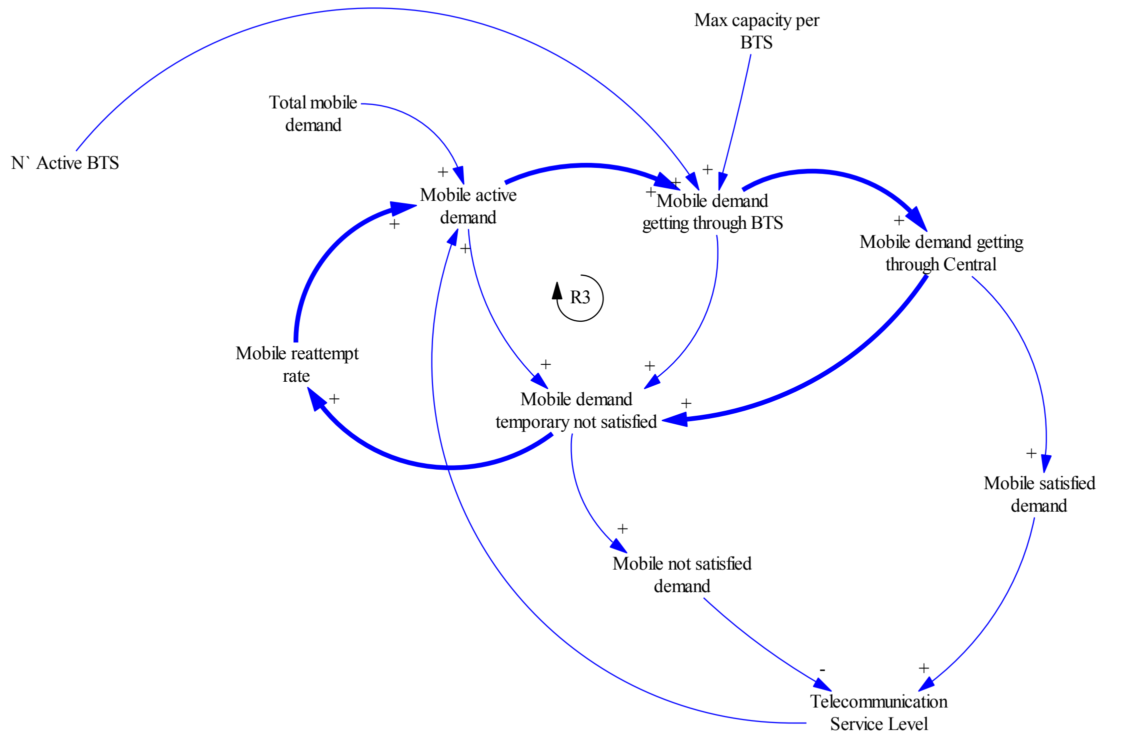

Figure 16: Centrals Bottleneck, Mobile Demand Not Satisfied

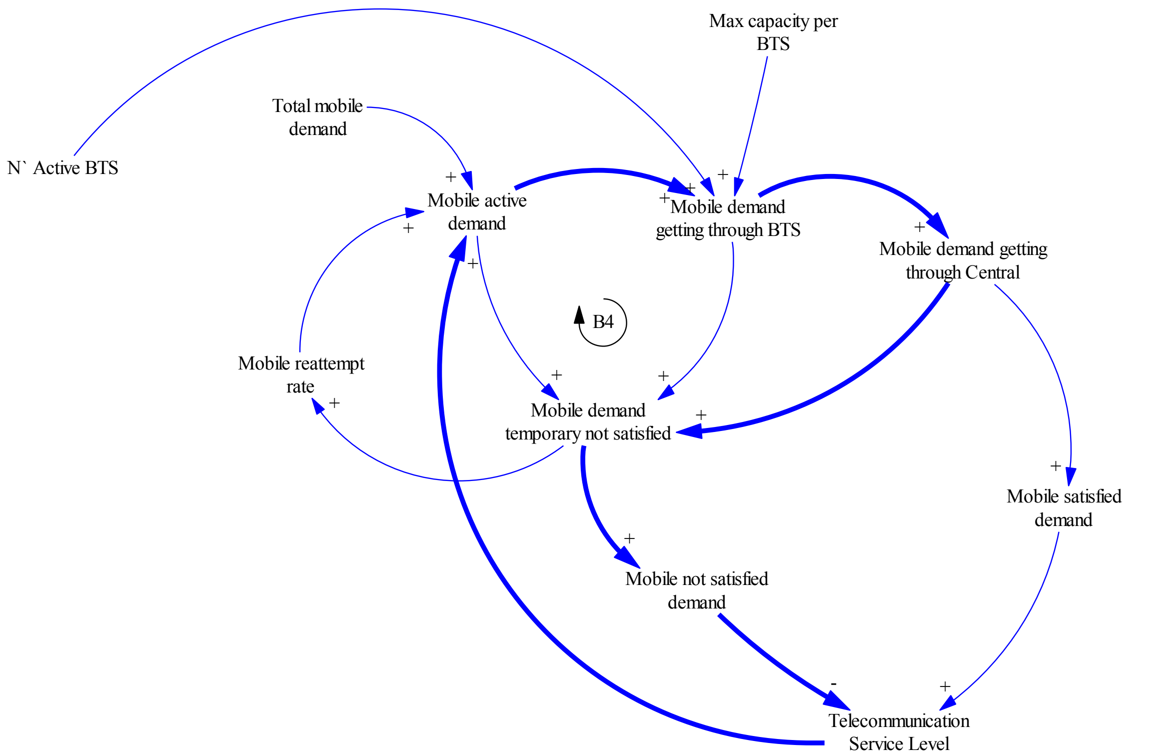

Figure 17: Full CLD of the Telecommunication Model

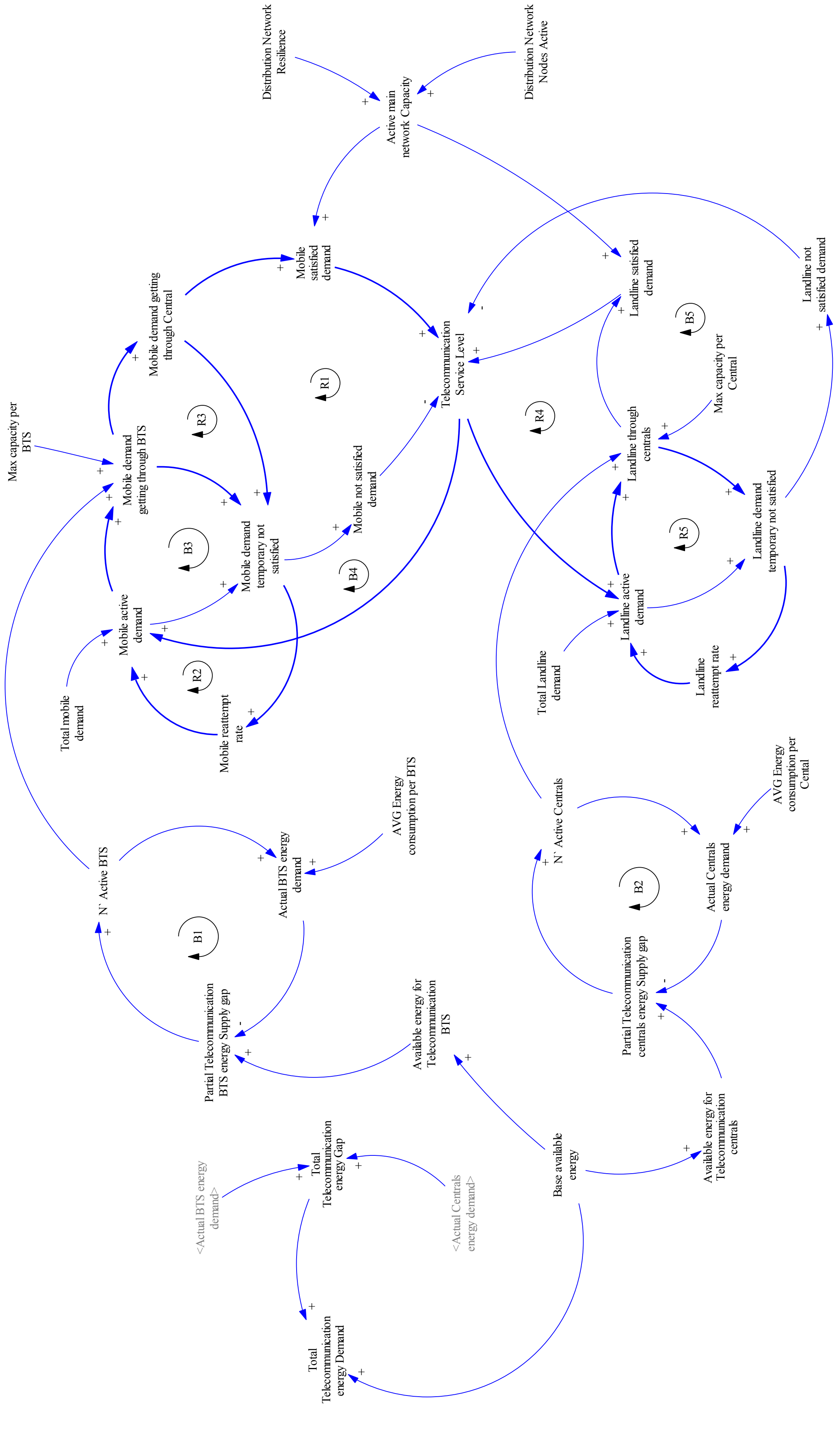

Figure 18: General Schema of a Subway Metropolitan System

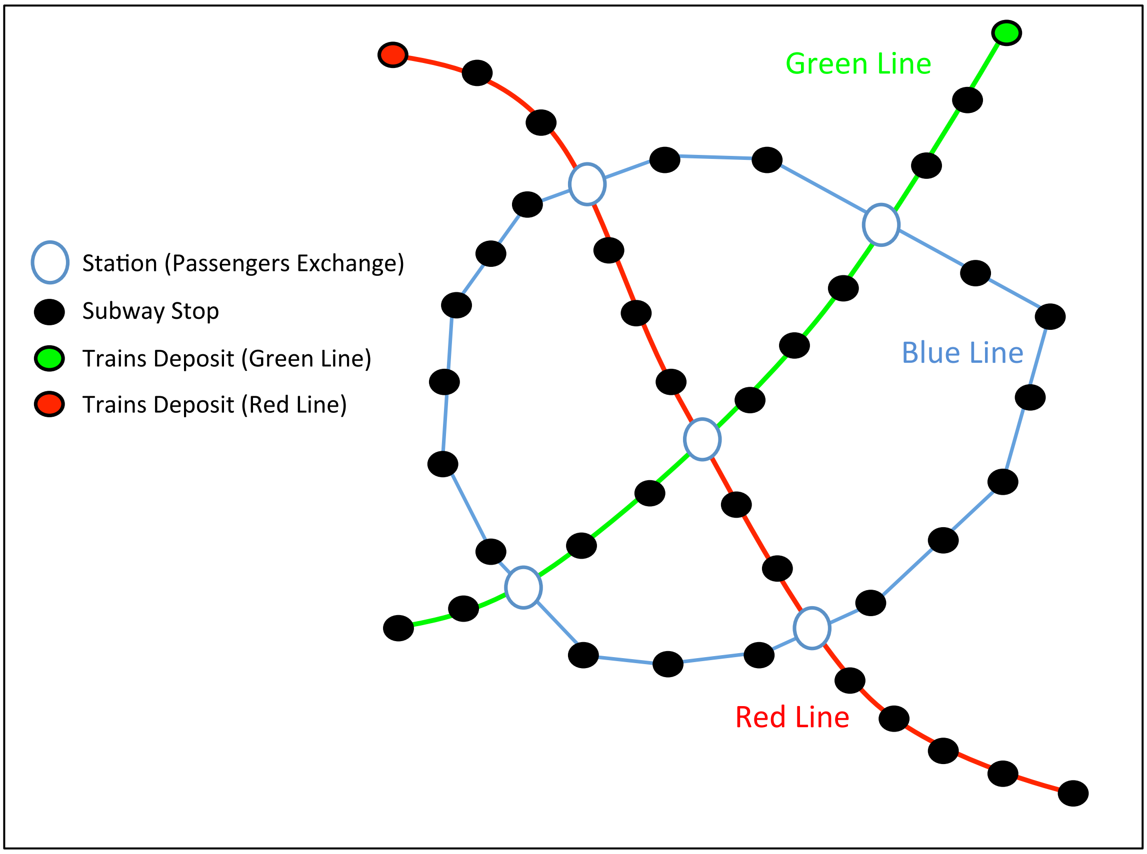

Figure 19: Processes in place inside a Subway Station or Stop

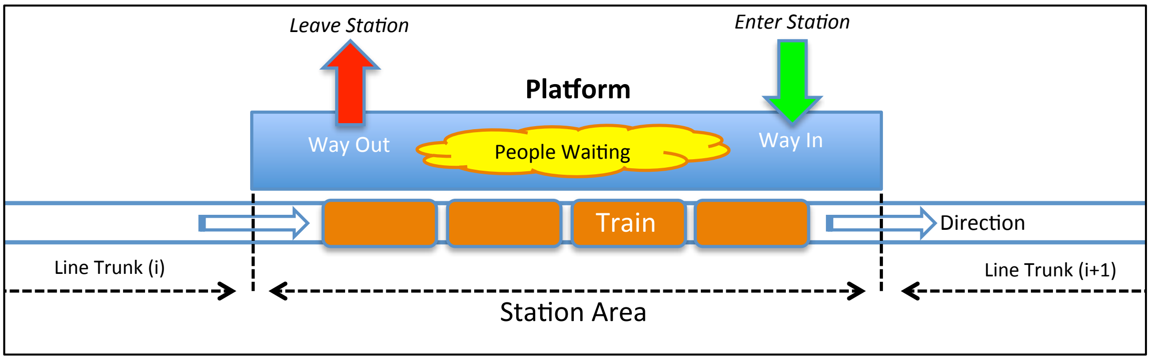

Figure 20: Stocks and Flows visualization of the Subway Subsystem

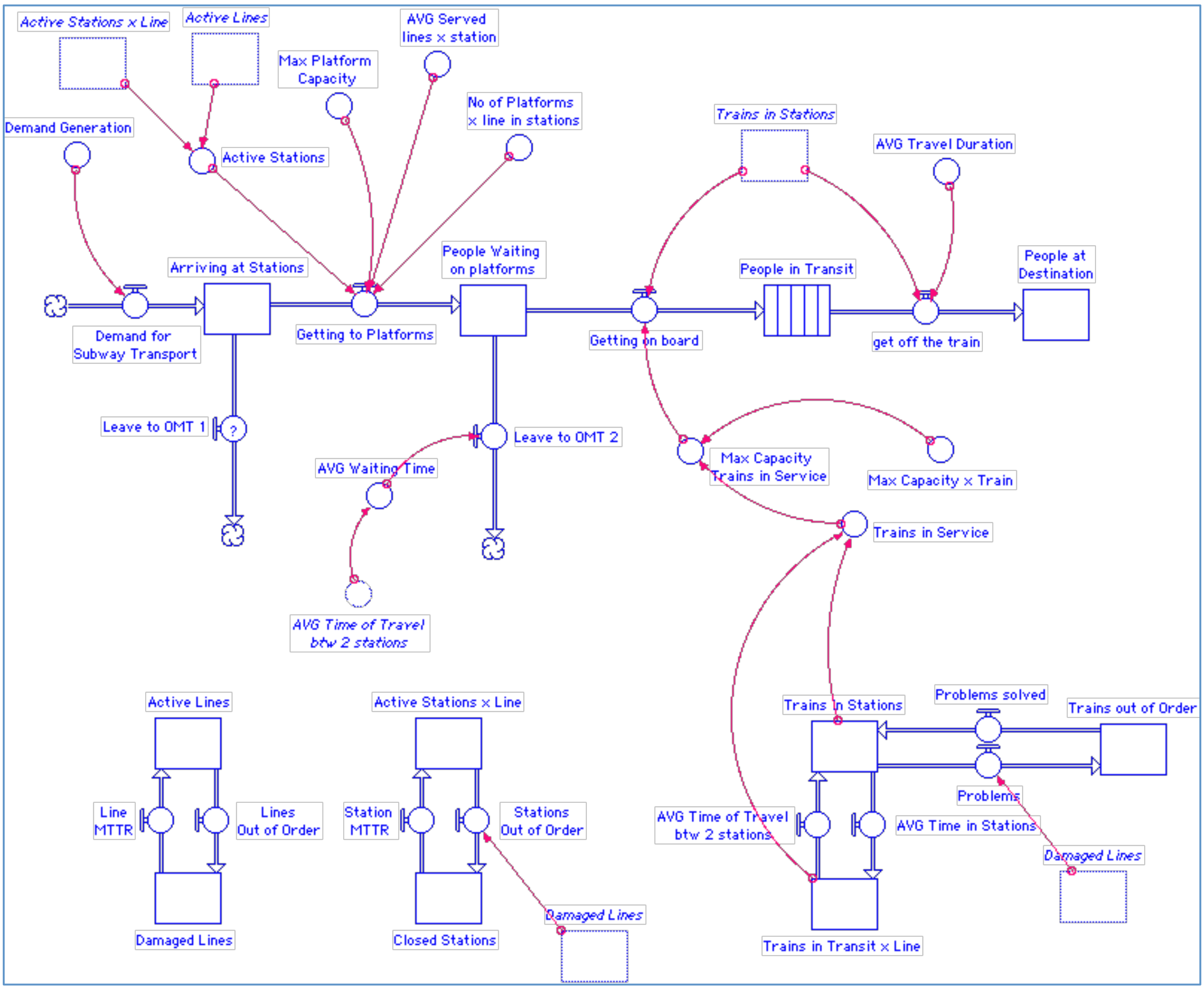

Figure 21: Stocks and Flows visualization of the Other Means of Transport (OMT) Subsystem

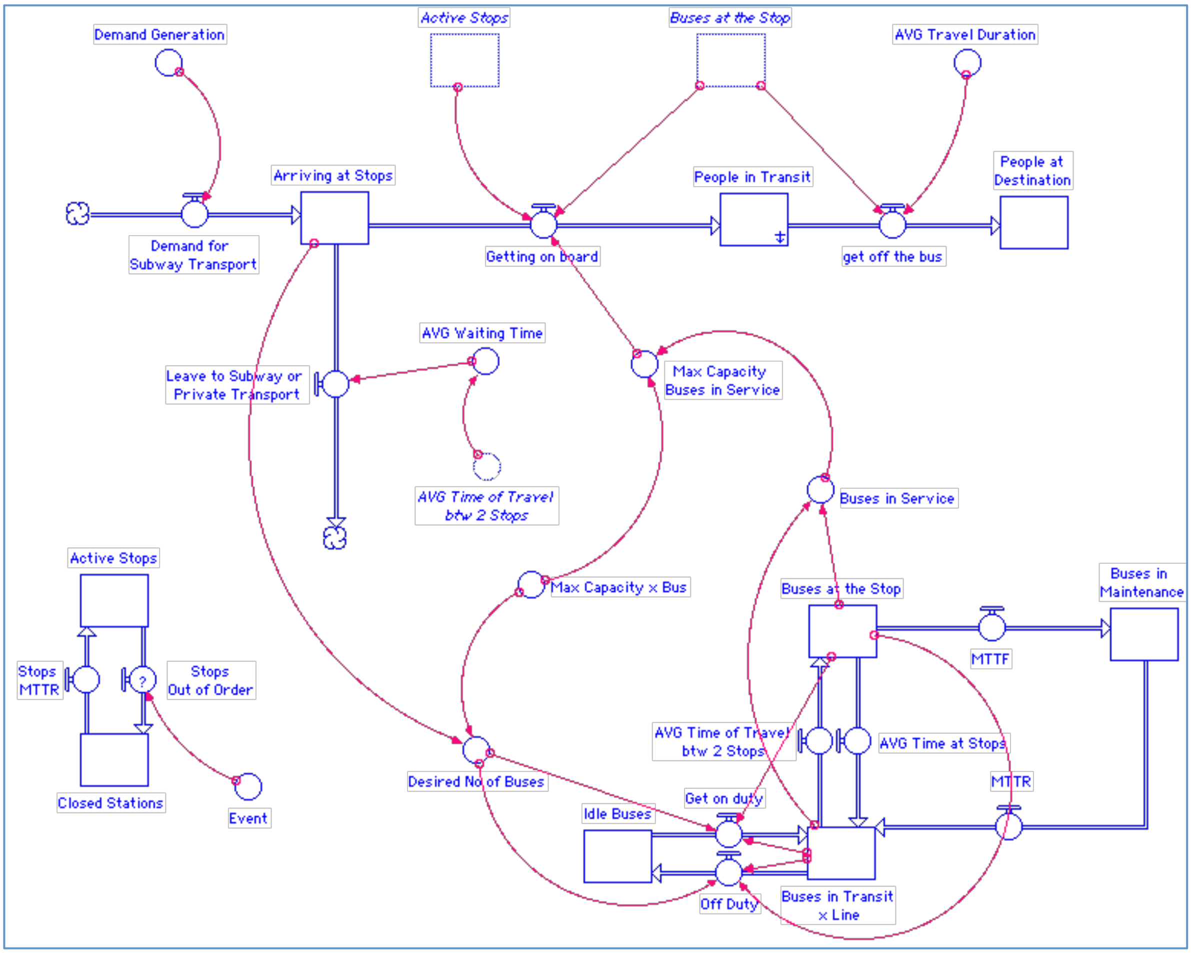

Figure 22: Stocks and Flows visualization of the Private Transportation Subsystem (with TRAFFIC KPI)