Norwegian University of Science and Technology

TPK5120
Elements of Model Engineering

Assignment 2: Review of all modelling formalisms

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Constraint satisfaction problem

Consider the problem of tiling a m * n checkerboard, i.e. completely and exactly covering it, with non-overlapping dominoes, i.e. 2 *1 rectangles.

Question 1: Propose a general formulation as a constraint satisfaction problem.

An m*n checkerboard is made of “mn” cells. To formulate this problem to find a pattern of filling in the dominoes, it is assumed that at least one of m or n is even, since this problem has a solution only when the value of *mn* is even. Since it needs to be tiled by dominoes of size 2 (since it is 2*1), we need *mn*/2 dominoes to cover the checkerboard exactly and completely.

A constraint satisfaction problem is a pair (V, C) where V is a finite set of variables and v is an element of V and C is the set of constraints. The possible values of v are given by domain of V.

For the question, the cells in the first row is labelled as 1 ,2, …., n; in the second-row n+1, n+2, …., 2n; and so on.
Each domino can be placed in any of these cells, so this means that the domain of possible values for the dominoes is given by [1, *mn*].
Each domino can be placed either horizontally or vertically. To answer the question each domino is divided into two. For example, consider domino 1. It is divided into 2: D_{1f} and D_{1s}, where D_{1f} represents the first cell domino is placed and D_{1s} represents the second cell the first domino is placed. The constraint placed on the second cell is in such a way that it can be placed either left/right (Horizontal) or above/below (vertical) from the first cell. For a checkerboard with n columns, every immediate cell above another will have a value +n , a cell below will have a value -n, a cell to the left has a value -1 and the one to the right has value +1.
For the first domino, the constraints are: -

$$D_{1f} - D_{1s} = n \text{ or } D_{1f} - D_{1s} = -n \text{ or } D_{1f} - D_{1s} = 1 \text{ or } D_{1f} - D_{1s} = -1$$

The constraints should be repeated for all the mn/2 dominoes.

Question 2: Apply it to a 5 *4 checkerboard. Find solutions with the algorithms implemented in Sherlock.

Now, we have a total of $5 \times 4 = 20$ cells and hence $20 \div 2 = 10$ dominoes, each with 2 parts. Next task is to modify the constraints so that it is readable in Sherlock.
The model for 5*4 is attached as “tiling5x4.csp" and in that case, the algorithm did not terminate. This could be due to the reason that “FindAllSolutions” search space becomes too large when the domain is as large as in this case. “FindOneSolution” algorithm was tried and the result is attached as “tiling5x4.txt”. The result basically conveys that the dominoes should be placed horizontally throughout the board. It is also worth noting that 10 choices were taken, which corresponds to 10 dominoes.
To find if the logic satisfies a smaller domain, the logic was tested for a 3*2 checkerboard, (refer model “tiling3x2.csp”). The solution is found in the folder solutions as “tiling3x2.txt” and this time the problem terminated. But, the number of solutions found were higher than expected. The problem identified was that there were a lot of copies, i.e., the same domino placed in the cell 3 and 4 is considered different from one placed in 4 and 3 according to the logic used. This could also have potentially led to the non-terminating issue with 5*4, hence more stringent constraints should be introduced to solve the question in hand.

Combinatorial Optimization Problem

The objective is to determine which pairs of components to connect so to minimize the total length of wire between components.

Question 3. Propose a formulation as a combinatorial optimization problem.

A combinatorial optimization problem is of the form (V, C, O),
where: V is a finite set of variables and $v \in V$. C is the set of constrain and O is the objective function. In the question it is said that the first component must be connected to the second component, the second to the third and so on. This is understood to mean that there is a connection between all the components at least indirectly and not more than 2 components will be connected to a component. With that understanding, the question is modelled by the following logic. The connection is assumed to be made of 5 wires, W1, W2, W3, W4 and W5. The idea behind the modelling is that, if the wire of a particular length is chosen after optimization, then that connection will be made. That is, for W1 if the length is decided to be 67, then connection between 1 and 2 will be made.

Set of possible values for each wire is set up using two variables, one for representing the wires W1, W2, W3, W4 and W5 and the other , labelled as L1, L2, L3, L4, L5 respectively for representing the possible lengths of each wire. Domain of values for all W's are [0,1] and. For the lengths, the domains are represented by the given table.

Length	Possible Values
L1	67, 52, 28, 56, 36
L2	67, 57, 73, 51, 32
L3	52, 57, 34, 84, 40
L4	28, 73, 34, 80, 44
L5	56, 51, 84, 80, 46

The set of constraints C are: -

1. All the wire should be connecting between different components. This is achieved by: -
    - W1 + W2 + W3 + W4 + W5 >= 15 and W1 + W2 + W3 + W4 + W5 <= 18 :- These constraints ensure that all the components are connected and at the same time a component already connected to twice is not connected again.
    - If W1 = 1, L1 = 67 else W1 = 2, L2 = 52 and so on: - Link the lengths to the appropriate wires and is repeated for all the wires

2. The length of all wires should be different *****. This is achieved by: -
    - L1! = L2! = L3! = L4! = L5

The objective function O is given by: -

Minimize L1 + L2 + L3 + L4 + L5

Remark (*): - The possible limitation with this logic is that it is dependent on the fact that the lengths between components are different. It will be a little confusing if the lengths between components are same. However, in electronics lengths are measures extremely accurately and hence the probability to have same length is assumed to be small and therefore it is proceeded with the logic.

Question 4. Solve this problem using Sherlock.

To solve the model using Sherlock, the constraints must be modified into sherlock identifiable language. The model is attached as “wiring.csp” and the solution observed is given in “wiring.txt”. Interpreting the solution from the lengths, the components must be connected in the following way, 1-6; 2-6; 3-4; 4-1; 5-2. The circuit is as shown below:

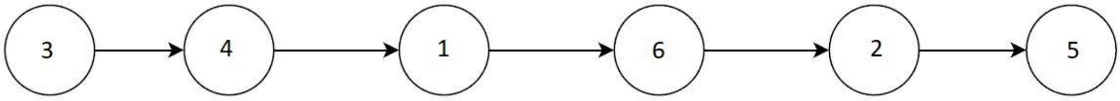

Figure 1: The optimized circuit

The length observed = 18.1mm

Testing examples (for question 3 and 4)

Example 1: The modelling was first done by assuming that more than two components could be connected to a single component. This was later regarded as not what is asked. This was done by not including the constraint “W1 + W2 + W3 + W4 + W5 >= 15 and W1 + W2 + W3 + W4 + W5 <= 18”. Nevertheless, the result obtained is attached. The model as “wiringTry1.csp” and the solution as “wiringTry1.txt” and the length now obtained was 17.6mm and the circuit as: -

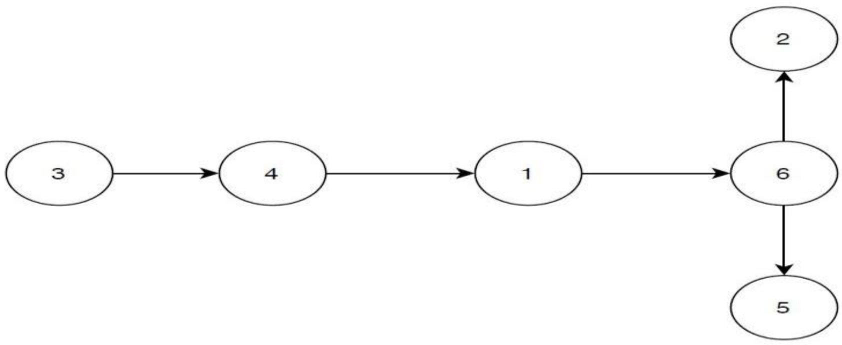

Figure 2: Circuit Try 1

Example 2: To remove the limitation mentioned in the remark of question 3, a different approach was tried and that is attached as “Approach2.csp” and the solution as “Approach2.txt”. The explanation is given in a document called “approach2.docx” inside the model folder. However, it was not possible to satisfy the assumption regarding the number of components connected to a component and got the same results as example 1 with length 17.6mm and therefore needs further investigation. Hence is it attached as an example only.

Remark: - In sherlock it was observed that decimal values does not work well, so the value was modified accordingly (5.2 into 52).

SYSTEM ARCHITECTURE

Consider the electric circuit of Airbus A320 as shown below: -

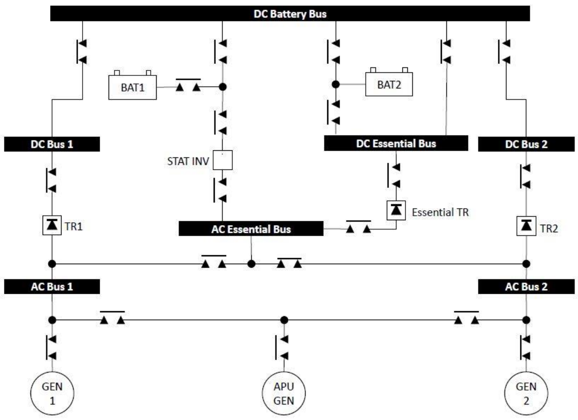

Figure 3: Circuit of the electrical system of Airbus A320

Question 5: Design an operational view of the system.

The operational analysis of the system is done to convey: -

1. What constitutes the system and what are the things in its immediate environment.
2. The life cycle of the system with its context of operation
3. How the system interacts with its environment

Environment

The system under analysis constitutes only the circuit that is given. All the other elements like the engine that powers the generator, pilot and the associated mechanism that controls the electric circuit and its load shedding and the other devices connected to the busbar, are all considered to be outside the system. Also, the analysis is done during flight and in that context operations like intensive maintenance is assumed to be outside the system. The elements like laws and regulations, airplane users and the design and production are also considered to get a global vision of the system and its environment. The block diagram that represents the system and its environment is given by: -

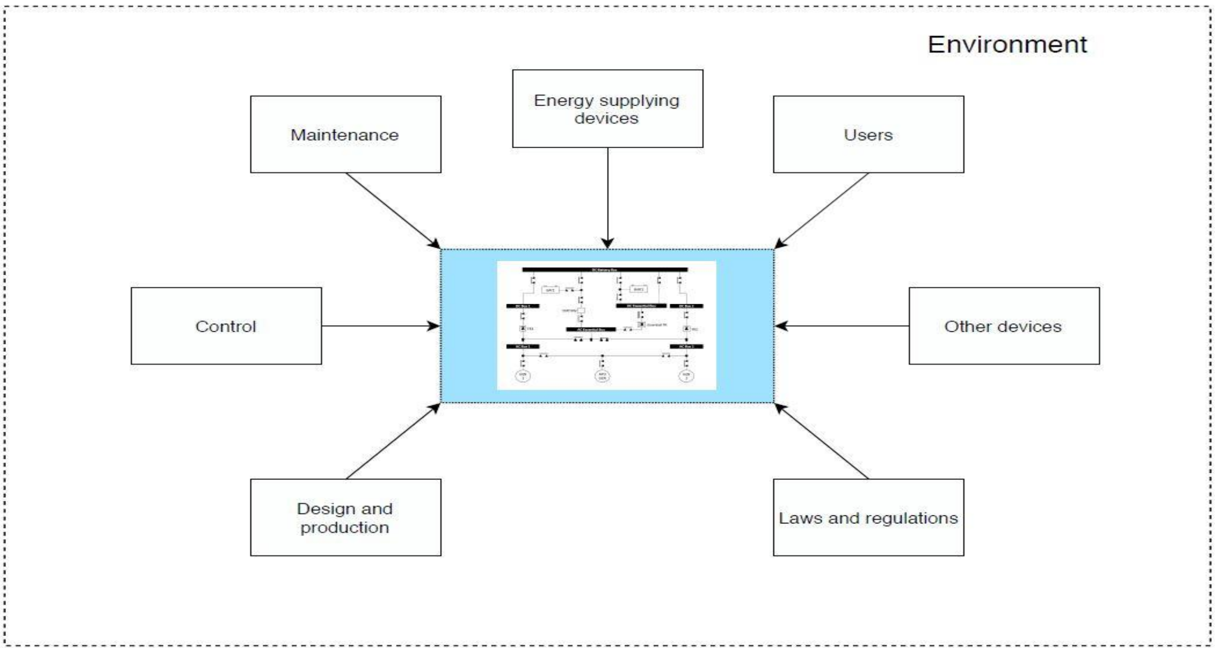

Figure 4: System and its environment

Life cycle analysis

The life cycle analysis gives information regarding the different modes of operation the system goes through in its operational phase. In this case the operation is restricted to flight only. Ideally the aircraft is said to have 5 phases of flight: Take-off, climb, cruise, descent, and landing. However, for the sake of simplification, climb is merged with take-off and descent with landing. some activities that takes place in the ground immediately before the flight, like last minute checks and troubleshooting is also considered to get a more comprehensive view.

General rules

- Gen 1 and Gen 2 have priority over APU.
- APU generator can supply whole network.
- Either of the generator can supply the whole network *.
- Generators cannot be connected in parallel.
- One of the batteries is sufficient to power both the essential bars.

Remark (*): = The term used in the question is major. Major is identified different from essential and in this context, major includes the whole network since o formal indication of what is major is given.

The different configurations of operation are: -

Normal configuration

In normal configuration, AC bus 1 and AC bus 2 is supplied by Gen 1 and Gen 2 respectively. AC bus 1 supplies the AC essential with the power when in normal operation. TR1, transforms the AC current into DC and powers the DC bar1, DC battery bus and DC essential bus. TR2 transforms the AC current and feeds it to DC bar 2. The 2 batteries that are connected to the DC battery bus if it needs to be charged.

Abnormal configuration

- ### Failure of one generator

The system replaces the failed generator with the other generator. Now, the AC bus1 and AC bus 2 is powered by the working generator and rest of the connection is same.

- ### Failure of both generator

The APU kicks in and starts supplying power to both the AC bus bars and subsequently the whole network.

- ### Failure at AC busbar 1

The AC busbar 2 will then supply the AC essential bus and the DC essential bus through the DC battery bus. It also powers the battery bus and the DC bus1.

- ### Failure at AC busbar 2

AC busbar1 powers DC busbar 2 through TR2.

- ### Failure of Transformer

The other transformer powers the DC battery bus and that powers the DC busbar 1.

- Failure of both transformer

Both the essential busbars will be powered by the generator through the essential transformer. However, connection to the DC buses and the DC battery bus is lost.

- Failure of all three generators.

The system runs on batteries. The battery supplies power to the AC essential and the DC essential through static inverter and essential transformer, respectively.

- Failure of generators and batteries

The system fails and the flight loses altitude dangerously leading to an accident.

The impact of each of the abnormal configuration could be classified into 3 broad categories according to the extent of the functional loss – small, medium, and severe. Example for small include failure at AC busbar 1, where only those devices connected to the busbar fails. Medium includes those that leads to all the non-essential functions being out of commission, like the failure of both the generator. Severe is the case when even the essential functions are out of operation and that occurs when the generators and the batteries have failed. The following state diagram gives an indication about the life cycle during flight: -

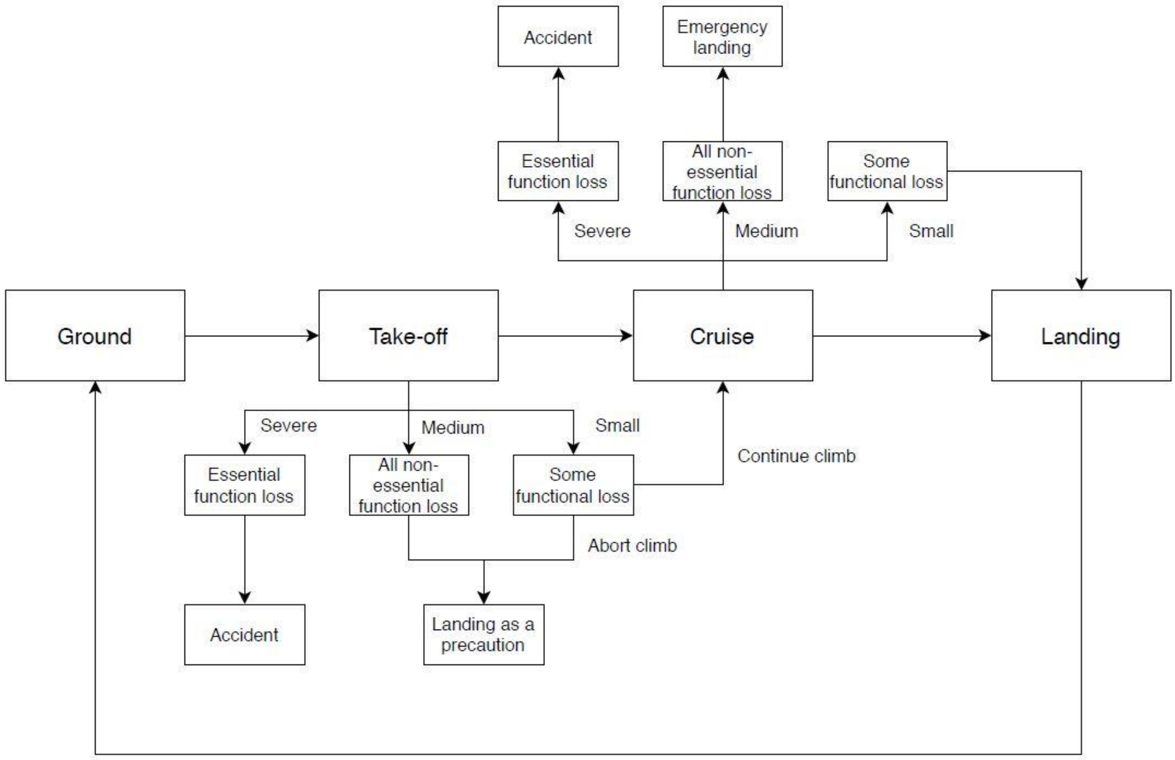

Figure 5 : State diagram for the different modes of operation

Consider that during take-off, small failure occurs, and the pilot observe some functional loss, he will take a decision, based on a multitude of factors like distance, weather condition etc. and also based on the inputs from the ground staff, whether to abort the climb or not. If the decision is to abort, it then lands as a precaution, otherwise it continues climb and later cruise.

Another scenario is that when in cruise, the pilot observe that a medium failure has occurred and now the plain is running on essential devices only. The pilot must contact the nearest airfield and do an emergency landing.
The overall state diagram of the system along with the interaction with the environment is the following:

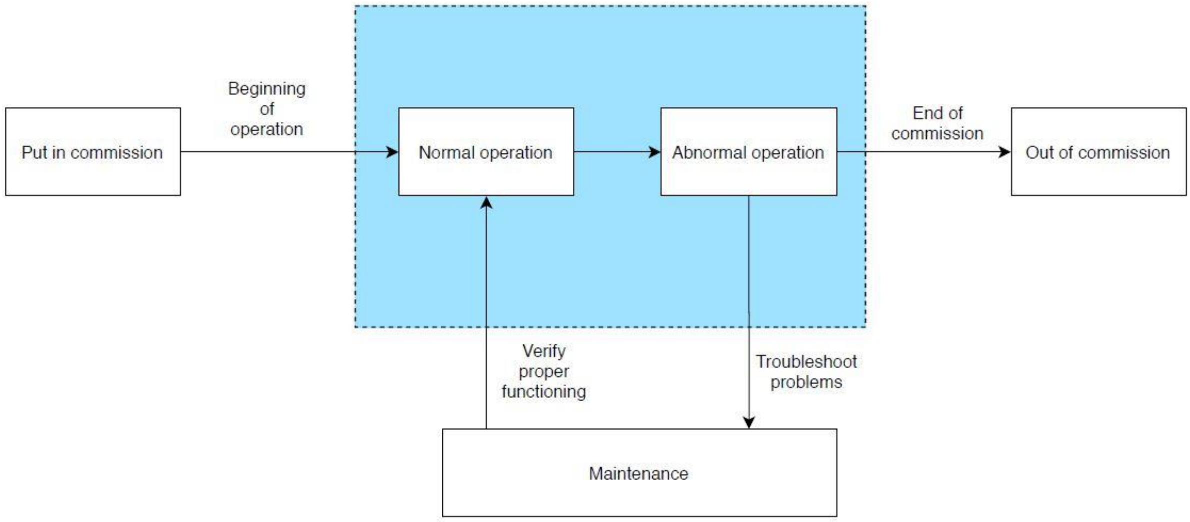

Figure 6: Overall state diagram

Question 6. Design a functional of the system.

The functional diagram of the system is as follows: -

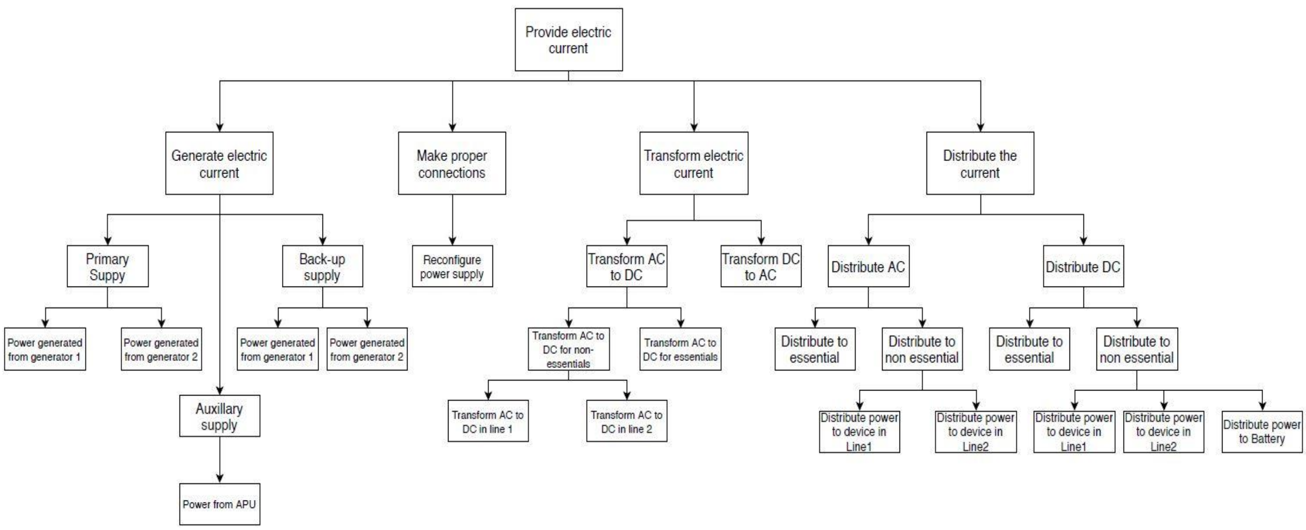

Figure 7: Functional diagram (refer pdf file named “functional diagram” for quality image)

Question 7. Design a physical view of the system.

The physical decomposition of the system is given. The decomposition is done according to the type of components

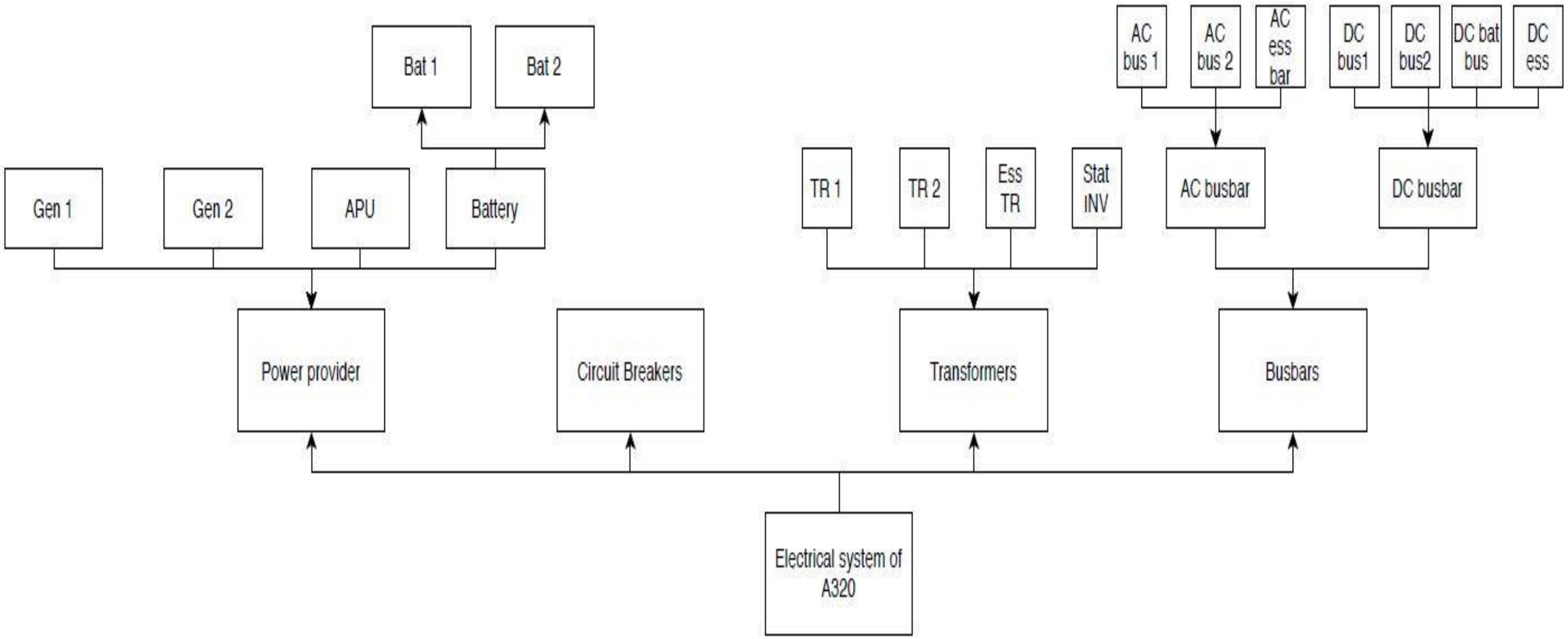

Figure 8: Physical decomposition

Question 8. Connect the functional and physical views.

The connected diagram is as below. The circuit breakers are connected directly without decomposing them.

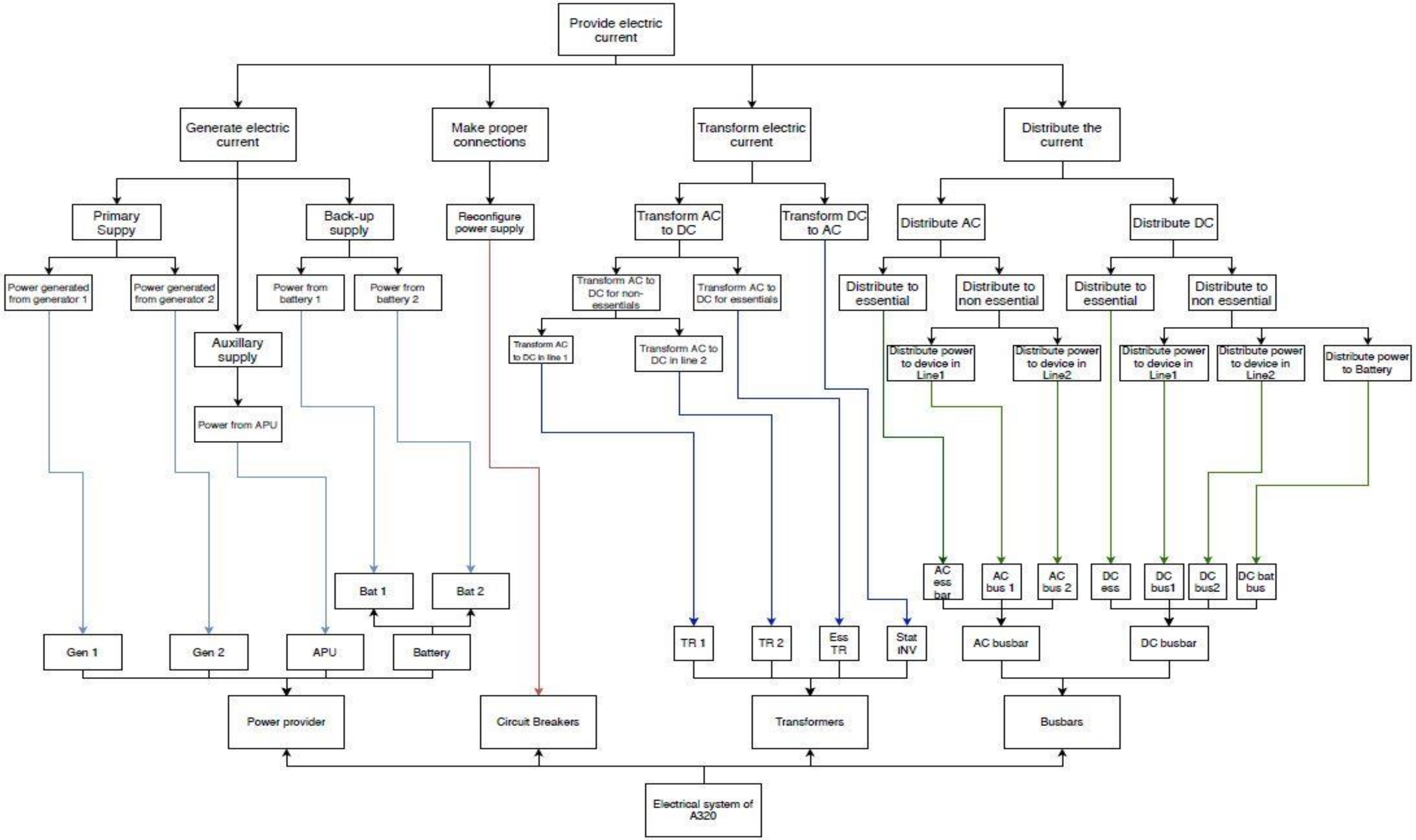

Figure 9: Connected diagram (refer "connected diagram.pdf")

Simulation

The aim is to simulate the different scenarios of the A 320 electrical system. Consider the following circuit for the following question.

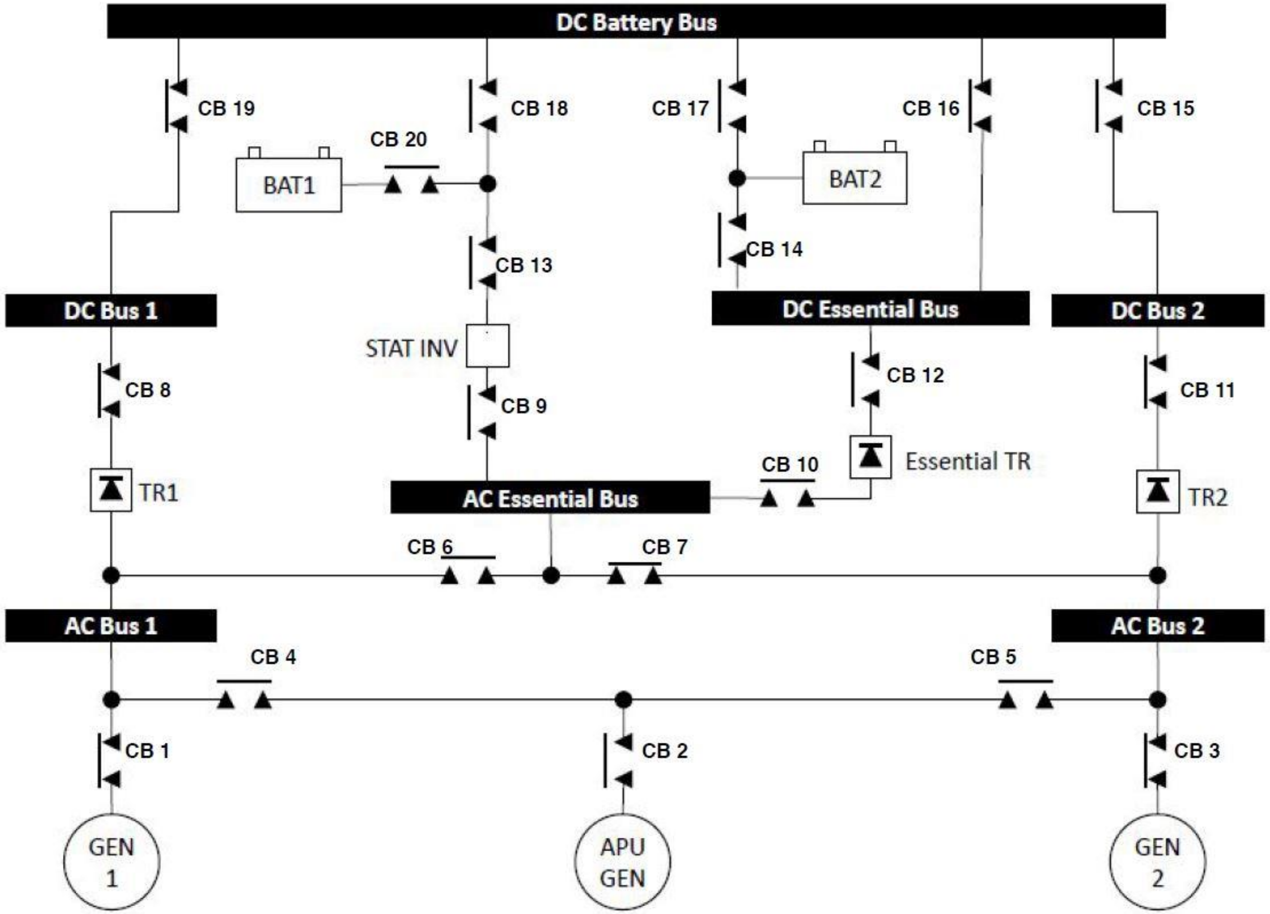

Figure 10: Circuit diagram with the CB's

Question 9. Design a Janos model that makes it possible to animate the functional and physical views of your architectural study.

Assumption: -

- The busbar can fail mechanically, due to phenomenon like snap, snag or also if the joint is loose. Such failures are assumed to be not present in the system to simplify the model as they are essentially not electrical failures and therefore does not fail.
- When the battery is not involved in power production, it is assumed to be in standby and charged continuously. Battery failed does not mean it is out of charge, it means it is no longer a valid electronic circuit.
- CB20 and CB17 allows flow in 2 direction.

Understanding of system working

Generator1 normally powers all the busbars except AC1 and DC2 which is powered by the other generator G2. If a failure occurs in, let us say generator X, then the other generator, Generator Y, takes over the whole circuit by connecting to both AC1 and AC2. If a failure occurs at both the Gen1 and Gen2, APU kicks in and that supplies the Access and DCess through AC1 and DCess. If a fault occurs in TR1, in any case, the DCess is powered through AC1 and DC2 (DC1 is lost in this case). If both TR1 and TR2 is lost, DCess is powered through ACess and Tress. If Tress is also failed, Battery 2 is put in operation, and that powers DCess.

If both generators and APU fails, batteries kick in and only the essential buses are powered. ACess is powered by Battery1 thorugh StatInv and the DCess is powered by Battery2. For this the CB20, assumed to allow flow in 2 directions, right to left when battery is in standby(charge) and left to right during running.

If Battery1 is failed, the Battery2 powers the StatInv through the Battery busbar and hence CB17 is also assumed to allow bi-directional flows. If the Bat 2 fails, Bat1 powers the ACess as said earlier and ACess subsequently powers DCess through TRess.

If each battery fails, the whole system fails.

The following distribution table is gives idea how the energy is supplied in different configuration: -

Config	AC bus1	AC bus 2	AC ess	Stat Inv	TR1	TR2	TR ess	DC bus1	DC bus2	DC bat bus	DC ess
Normal	Gen 1	Gen 2	Gen 1	-	AC bus1	AC bus2	-	TR1	TR2	TR1	DC bat bus
One gen fail	Other Gen	Other Gen	Other Gen	-	AC bus1	AC bus2	-	TR1	TR2	TR1	DC bat bus
Both Gen fail	APU	APU	APU	-	AC bus1	AC bus2	-	TR1	TR2	TR1	DC bat bus
Gens and APU fail	-	-	Stat Inv	Bat 1	-	-	-	-	-	-	Bat 2
Gens, APU and Battery 1 fail	-	-	Stat Inv	DC bat bus	-	-	-	-	-	Bat2	Bat 2
Gens, APU and Battery 2 fail	-	-	Stat Inv	Bat 1	-	-	AC ess	-	-	Bat1	TR ess

The janos model that has been modelled has been attached as “A320.dfe” and “A320.janos”. An instance of the result when all the generators have been failed and the system running on batteries is provided as “A320simulationResult.csv”. The model has been tested to verify if it behaves as in the table above. The model was tested for different scenarios like failure of the 2 primary transformers along with the TR ess; Failure of all generators, battery1 and static inverter and the behaviour was as expected at those times. The model could be tested by changing the state of the components. The model also checks for short-circuit at different busbars.

Remark: - The DC bus1 and DC bus 2 was not checked for short circuit since it has only one direct connection.

The combination of block was found to be not efficient when testing, however it was proceeded with since it satisfies the function. In future, it must be kept in mind to block more appropriately to facilitate easier testing.

Also, in the model there are classes called SpecialCircuitBreaker and BatteryBusbar. These are not different from other circuit breakers or busbars, but they have flow in two direction and hence is modelled using a different class.

Circuit breaker failures are very prevalent in such a circuit; however, the aim of the question is to animate the functional and physical view and hence they are not tested by changing their states. The model identifies how the power will be distributed under different configuration.

Many scenarios were later identified when safety analysis was done, the conditions for this were not incorporated in the circuit breakers and hence this is a flaw in the model. In future, the fault tree analysis should be done before doing the simulation.

Safety analysis

The aim is to complete the study with a safety analysis.

Question 10. Design a Cassis model to implement your safety study.

Safety study

The first step undertaken in the safety study was to identify the failure modes of each component. Some failure modes like operator negligence are not considered since they are out of the system bounds. The different failure modes of each components are listed as below: -

Generator

1. Fault in the transmission system from the engine leading to the rotor not moving.
2. Varying voltage or no voltage produced by the generator. This could be due to: -
    - Insulation failure in the generator.
    - Cavitation in the rotors.
    - Stator wiring failure.

Transformer

1. The contactor of transformer opens when there is: -
    - Overheat
    - Less than minimum current
2. The transformer fails if its insulation fails.

Inverter

Though in the previous models they are considered as the “class” of component, their modes of failure are different. They are: -

1. Over or under-voltage.
2. Capacitor wear.

Battery

The batteries in A320 are named Skyzen provided by Saft and are essentially Nickel-Cadmium cells. The failure modes are: -

1. There is an internal short circuit in the battery
2. The charge in the battery is depleted due to: -
   - Contamination
   - Overuse

Circuit breakers

The circuit breaker fails in 3 ways: -

1. Fail to open.
2. Fail to close
3. Fail to remain closed or open

Cassis model

Following assumptions are used in the model: -

1. The failure rate of the components is given one failure rate which is a representation of the aggregate of the different failures as mentioned above.
2. Circuit breaker fails in the three ways mentioned above. There are 20 CB's in the circuit and for the purpose of reducing complexity, instead of considering them in the circuit they are considered as a different element which can fail on demand and in use.
3. The busbars are considered in the circuit to show the dependencies, however, unlike before they are given failure rates.
4. If either of the essential system fails (AC or DC), we lose the aircraft.
5. Though the load on different components are different all identical components are given same failure rate

Fault tree

Since we lose the aircraft when we lose any of the essential function, a fault tree is made with that consideration, instead of using the functional and physical architecture made above. The fault tree is as below: -

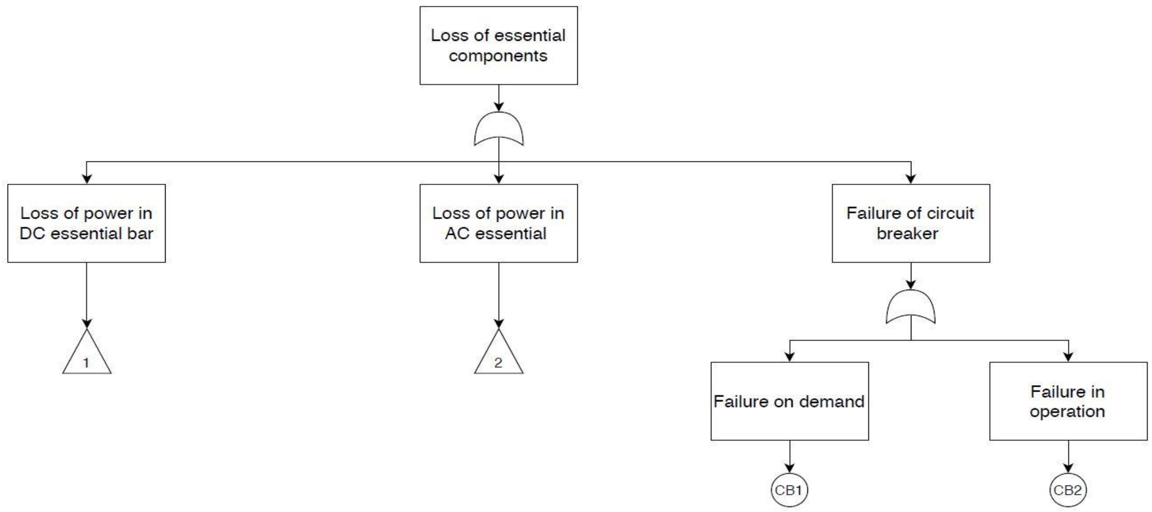

Figure 11: Fault tree

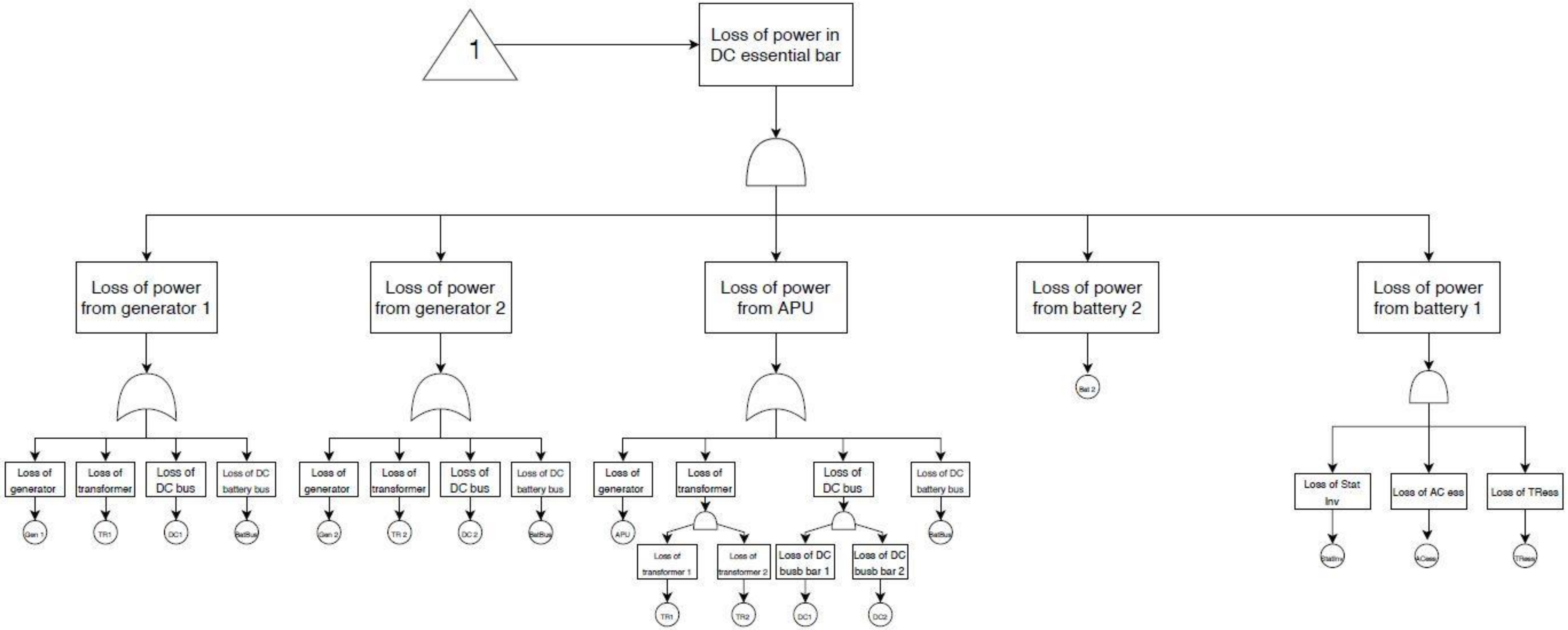

Figure 12: Fault tree contd. (refer "Fault tree DCess.pdf")

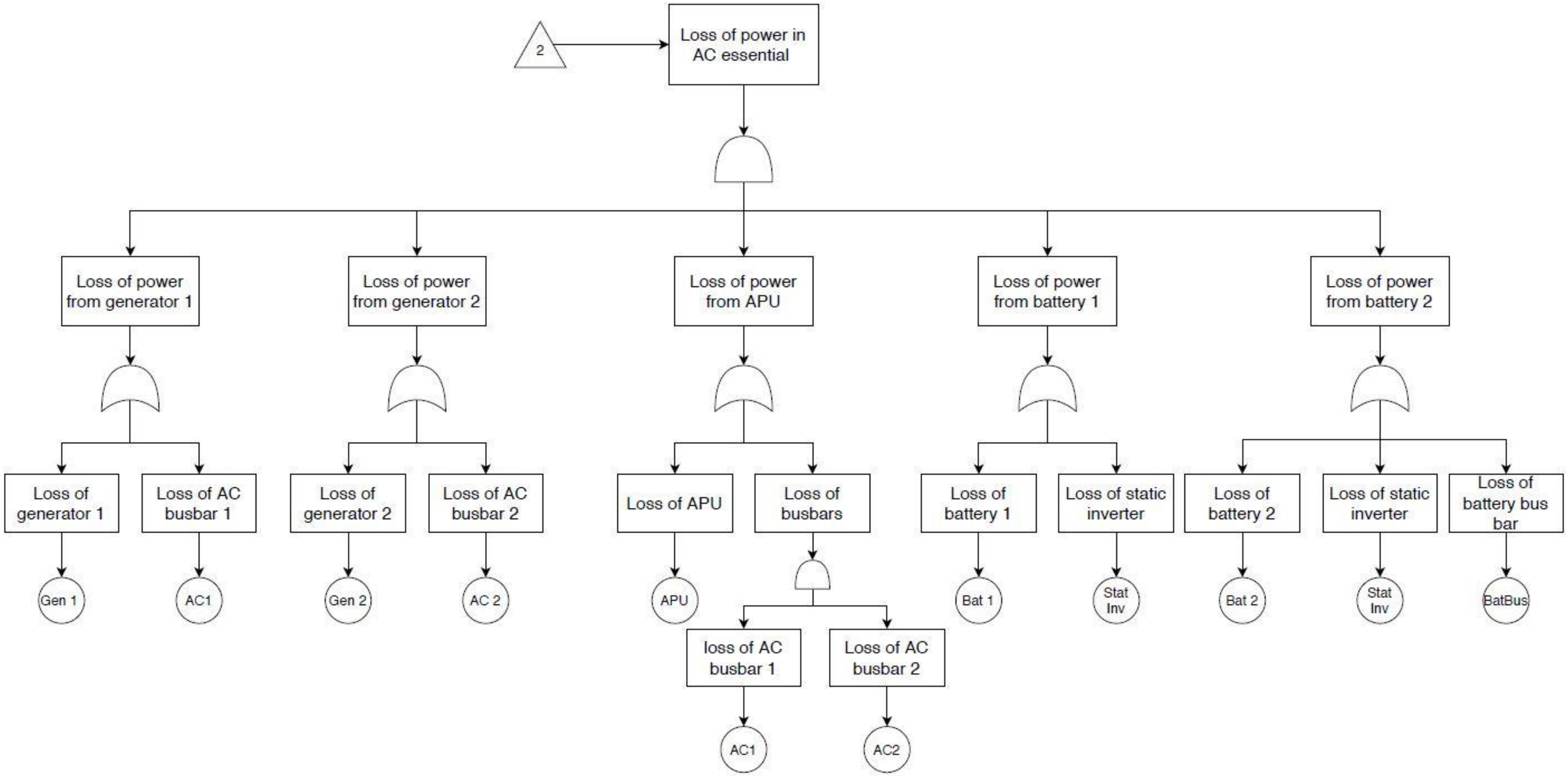

Figure 13: Fault tree contd.

The fault tree was modelled into the cassis and is attached as “A320.pbc” and the script file as “A320.cassis”. The top event probability obtained from the arbitrarily set values for 8760 hrs of operation was 7.3394e-05. The result text file is attached as “A320 electric system failure.txt”.

Remarks: - The effectiveness of the model is affected by the assumption 2, since the circuit breaker failure rate was found to affect the probability of events a lot.

Question 11. Extract minimal cutsets from this model.

The minimal cutsets extracted from the model is as shown below: -

```
Variable    LossOfelectricalSystem
Handle  ZBDD-MCS
Product
Gen1.failed BatBus.failed   Gen2.failed APU.failed  Bat1.failed
Gen1.failed BatBus.failed   APU.failed  AC2.failed  Bat1.failed
Gen1.failed Gen2.failed APU.failed  Bat2.failed Bat1.failed
Gen1.failed Gen2.failed APU.failed  StatInv.failed
Gen1.failed APU.failed  Bat2.failed AC2.failed  Bat1.failed
Gen1.failed APU.failed  StatInv.failed  AC2.failed
AC1.failed  BatBus.failed   Gen2.failed APU.failed  Bat1.failed
AC1.failed  BatBus.failed   AC2.failed  Bat1.failed
AC1.failed  Gen2.failed APU.failed  Bat2.failed Bat1.failed
AC1.failed  Gen2.failed APU.failed  StatInv.failed
AC1.failed  Bat2.failed AC2.failed  Bat1.failed
AC1.failed  StatInv.failed  AC2.failed
BatBus.failed   Bat2.failed StatInv.failed
BatBus.failed   Bat2.failed ACess.failed
BatBus.failed   Bat2.failed TRess.failed
CBs.FailOnDemand
CBs.FailInOperation
```

Figure 14: MCS from cassis

A total of 15 scenarios were obtained, excluding the circuit breaker scenario. The circuit breaker scenario is not modelled properly as mentioned as is just an indication that the electrical system loss can occur if the circuit breakers fails to operate as expected. The text file is attached as “mcsA320-modified.txt”.

Remark: - To better understand the model some modifications was made to the system from question 9 when modelling for cassis. For instance, here it was assumed that the battery 1 can power DC essential bar through DC battery bus if battery 2 is failed. This proved to be effective as the number of cutsets decreased. This also helped to eliminate the dependency on the transformers TR1 and TR2 as seen from the MCS above, where they play no role. The MCS without the modification is shown. The possibility of this is in the actual world was not investigated and was done just as a learning process. The original result is attached as “mcsA320-original.txt”.

```
Variable    LossOfelectricalSystem
Handle  ZBDD-MCS
Product
Gen1.failed BatBus.failed   Gen2.failed APU.failed  Bat1.failed
Gen1.failed BatBus.failed   APU.failed  AC2.failed  Bat1.failed
Gen1.failed Gen2.failed APU.failed  Bat2.failed ACess.failed
Gen1.failed Gen2.failed APU.failed  Bat2.failed TRess.failed
Gen1.failed Gen2.failed APU.failed  Bat2.failed Bat1.failed
Gen1.failed Gen2.failed APU.failed  StatInv.failed
Gen1.failed APU.failed  Bat2.failed AC2.failed  Bat1.failed
Gen1.failed APU.failed  StatInv.failed  AC2.failed
AC1.failed  BatBus.failed   Gen2.failed APU.failed  Bat1.failed
AC1.failed  BatBus.failed   AC2.failed  Bat1.failed
AC1.failed  Gen2.failed APU.failed  Bat2.failed Bat1.failed
AC1.failed  Gen2.failed APU.failed  StatInv.failed
AC1.failed  APU.failed  Bat2.failed StatInv.failed
AC1.failed  APU.failed  Bat2.failed ACess.failed
AC1.failed  APU.failed  Bat2.failed TRess.failed
AC1.failed  Bat2.failed AC2.failed  Bat1.failed
AC1.failed  StatInv.failed  AC2.failed
TR1.failed  APU.failed  Bat2.failed StatInv.failed
TR1.failed  APU.failed  Bat2.failed ACess.failed
TR1.failed  APU.failed  Bat2.failed TRess.failed
TR1.failed  TR2.failed  Bat2.failed StatInv.failed
TR1.failed  TR2.failed  Bat2.failed ACess.failed
TR1.failed  TR2.failed  Bat2.failed TRess.failed
DC1.failed  APU.failed  Bat2.failed StatInv.failed
DC1.failed  APU.failed  Bat2.failed ACess.failed
DC1.failed  APU.failed  Bat2.failed TRess.failed
DC1.failed  DC2.failed  Bat2.failed StatInv.failed
DC1.failed  DC2.failed  Bat2.failed ACess.failed
DC1.failed  DC2.failed  Bat2.failed TRess.failed
BatBus.failed   Bat2.failed StatInv.failed
BatBus.failed   Bat2.failed ACess.failed
BatBus.failed   Bat2.failed TRess.failed
CBs.FailOnDemand
CBs.FailInOperation
```

Figure 15: MCS without modification

Maximum Flow Problem

Question 12. Propose a formulation as a maximum problem. Draw the directed graph and put the edge capacity above each edge

A maximum flow problem is a network of the form N (V, E), where V is the set of vertices and E is the set of edges. Each edge, $e \in E$ has a capacity C(e) which is the maximum flow that can pass through the edge e.

In the given question the set of nodes, V = {Source, sA, sB, sO, sAB, tA, tB, tO, tAB, Target}

The edges are, E = { s→sA, s→sB, s→sO, s→sAB, sA→tA, sA→sAB, sB→tB, sB→sAB, sO→tA, sO→tB, sO→tO, sO→tAB, , sAB→tAB, tA→t, tB→t, tO→t, tAB→t}}

Although there is no capacity limit as identified from the question for some edges, the limit is set to be the maximum of the flow possible from the immediately preceding node if there are no set limits. The set of capacities are: -

C(s→sA) = 46
C(s→sB) = 34
C(s→sO) = 45
C(s→sAB) = 45
C(sA→tA) = 46
C(sA→sAB) = 46
C(sB→tB) = 34
C(sB→sAB) = 34
C(sO→tA) = 45
C(sO→tB) = 45
C(sO→tO) = 45
C(sO→tAB) = 45
C(sAB→tAB) = 45
C(tA→t) = 39
C(tB→t) = 38
C(tO→t) = 42
C(tAB→t) = 50

The directed graph is as follows: -

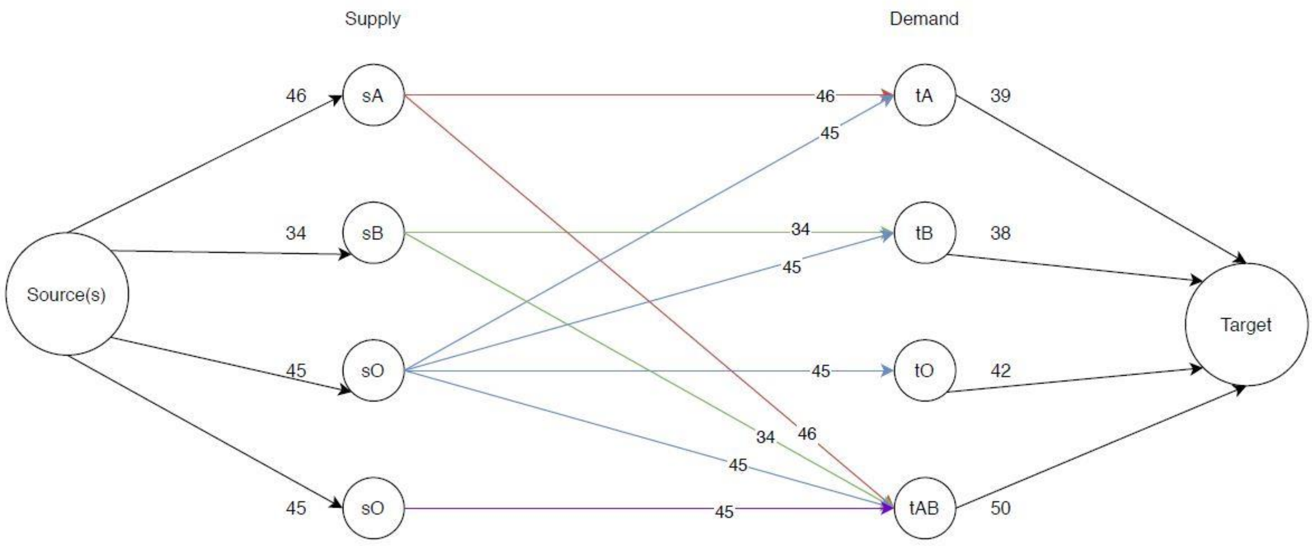

Figure 16: Flow diagram

Question 13. Solve this problem using Edgser.

The problem has been modelled using Edsger and has been attached as “BloodSupply.net” along with the script file “BloodSupply.edsger”. The result obtained is attached as “BloodSupplyResult.txt”.

```
Model   Transfusion
source  s
target  t
node    flow
s   168.0
sA  46.0
sB  34.0
sO  45.0
sAB 43.0
tA  39.0
tB  38.0
tO  41.0
tAB 50.0
t   168.0
edge    source  target  capacity    flow
e1  s   sA  46.0    46.0
e2  s   sB  34.0    34.0
e3  s   sO  45.0    45.0
e4  s   sAB 45.0    43.0
e5  sA  tA  46.0    39.0
e6  sA  tAB 46.0    7.0
e7  sB  tB  34.0    34.0
e8  sB  tAB 34.0    0.0
e9  sO  tA  45.0    0.0
e10 sO  tB  45.0    4.0
e11 sO  tO  45.0    41.0
e12 sO  tAB 45.0    0.0
e13 sAB tAB 45.0    43.0
e14 tA  t   39.0    39.0
e15 tB  t   38.0    38.0
e16 tO  t   42.0    41.0
e17 tAB t   50.0    50.0
```

Figure 17: Snapshot of the result

The outcome is that 168 patients will get the required blood from the clinic and there will be one remaining patient who cannot be serviced using the available unit of blood. Blood sample O is of insufficient stock with only 41 units being able to be supplied.

Remark: - The edge capacity can be given any arbitrary high values, like 100 or 500 for instance. The shortage could have occurred for either sample B or sample O. It is dependent on the placement of the line setting up the allocation in the ".net" file, which essentially means the sequence of entering the algorithm. The result file is attached as "BloodSupplyResultwithShortageAtB.txt".

```
Model   Transfusion
source  s
target  t
node    flow
s   168.0
sA  46.0
sB  34.0
sO  45.0
sAB 43.0
tA  39.0
tB  37.0
tO  42.0
tAB 50.0
t   168.0
edge    source  target  capacity    flow
e1  s   sA  46.0    46.0
e2  s   sB  34.0    34.0
e3  s   sO  45.0    45.0
e4  s   sAB 45.0    43.0
e5  sA  tA  46.0    39.0
e6  sA  tAB 46.0    7.0
e7  sB  tB  34.0    34.0
e8  sB  tAB 34.0    0.0
e9  sO  tA  45.0    0.0
e11 sO  tO  45.0    42.0
e10 sO  tB  45.0    3.0
e12 sO  tAB 45.0    0.0
e13 sAB tAB 45.0    43.0
e14 tA  t   39.0    39.0
e15 tB  t   38.0    37.0
e16 tO  t   42.0    42.0
e17 tAB t   50.0    50.0
```

Figure 18: Snapshot of shortage at B

Future Works

1. To solve the issue the non-terminating issue in question 2, the idea is to completely alter the logic in such a way that it restricts the domain. One idea is to restrict the domain to 0 and 1, which represents either horizontal or vertical placement and then proceed to introduce constraints into where the domino could be placed in the cells.
2. In the wiring problem, approach 2 could be refined by introducing constraints that limits the maximum connection to a component to 2.
3. For question 9, the model should be modified to include all the logical constraints for the circuit breakers and the states of the busbars.
4. For the safety study, more articles should be read about how different components could fail. The listed is most probably just a small subset of the actual cases,
5. In the Cassis model, the circuit breakers are modelled in a limited way. One way to better the model is to introduce those for individual connections.