Appendix A

Example Engine Cycle Schemes

In this appendix some example engine cycles are given to give the user an idea of the possible engine architectures and varieties that are supported in LiRA. Figures A-1 to A-6 show a pressure fed cycle, a gas generator cycle, two staged combustion cycles, a closed expander cycle and a bleed expander cycle. Two staged combustion cycles are shown to show the difference in engine architecture when the user chooses for the fuel rich or for the oxygen rich pre-burner; when a fuel rich pre-burner is chosen the assumption is made that most of the fuel remains unburned after passing the pre-burner and the oxidiser content is so little that the gas flow after passing the turbine can be considered a pure fuel flow and thus only oxidiser needs to be added in the main combustion chamber. For oxygen rich pre-burners the same is true except now the flow behind the turbine is assumed to be so rich in oxygen that the fuel content is negligible and only fuel in the main combustion chamber must be added. Further the example cycles also show the variety of using a single or double turbine; note that only parallel double turbines are supported not series. Some examples have regenerative cooling of both combustion chamber and nozzle, while others have only regenerative cooling of the main combustion chamber or no regenerative cooling at all. Currently LiRA does not allow for nozzle cooling without chamber cooling and no dump cooling neither.

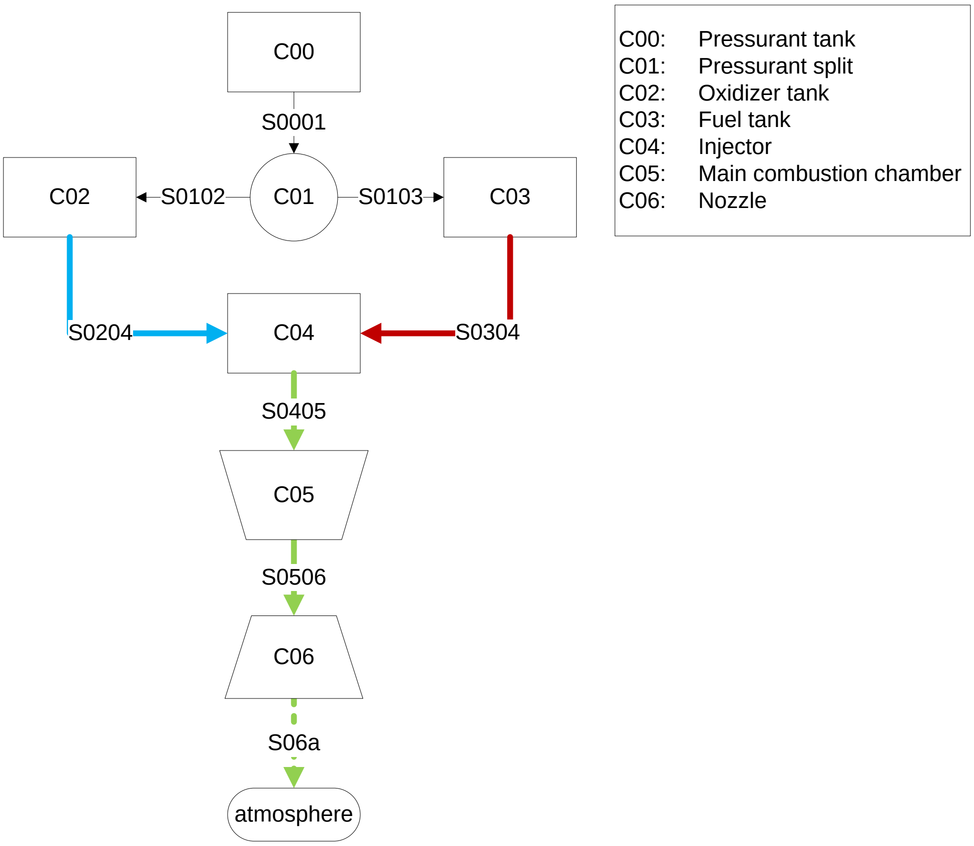


Figure A-1: pressure fed cycle with no regenerative cooling

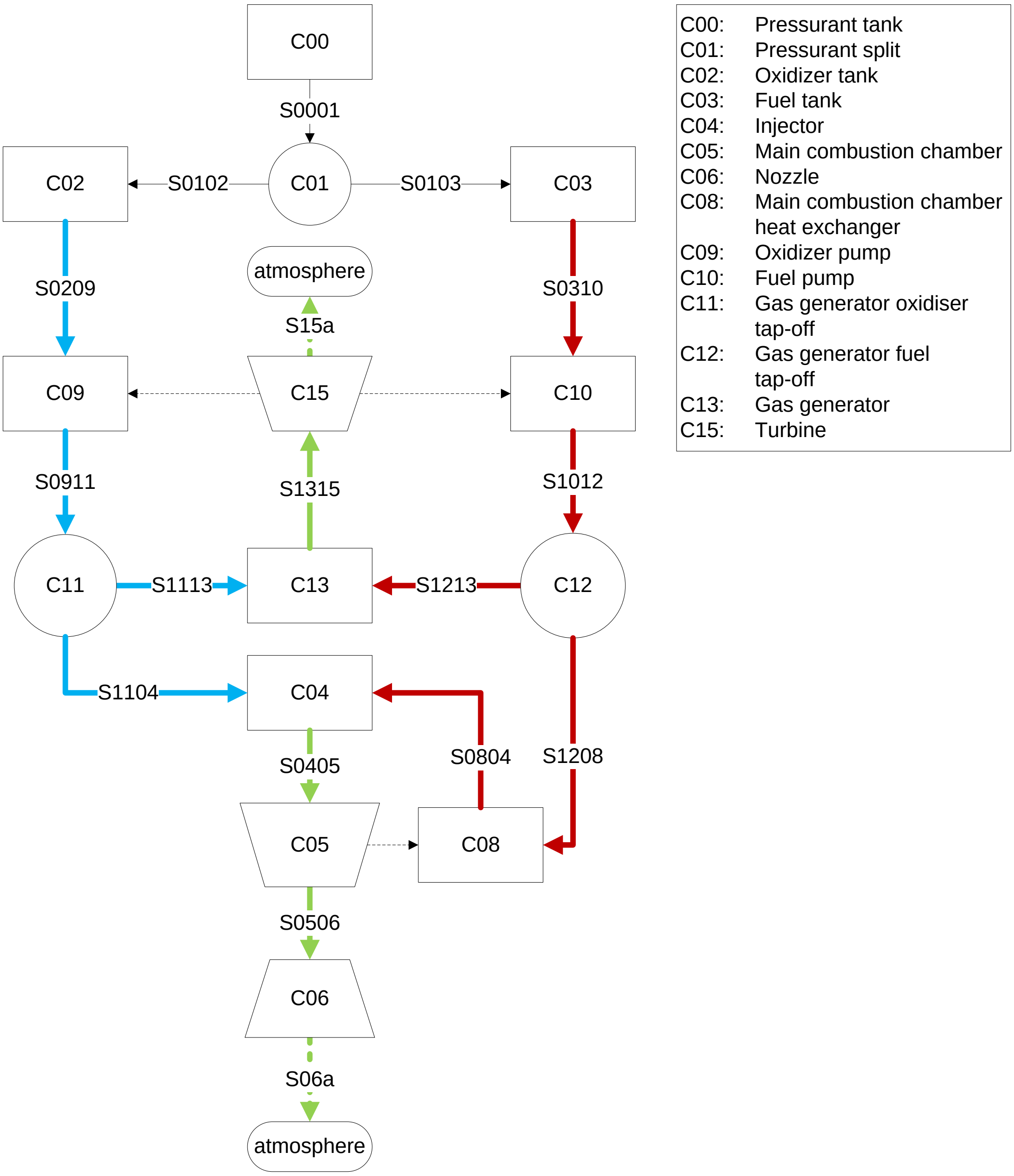


Figure A-2: Gas generator cycle with a single turbine with regenerative chamber cooling only

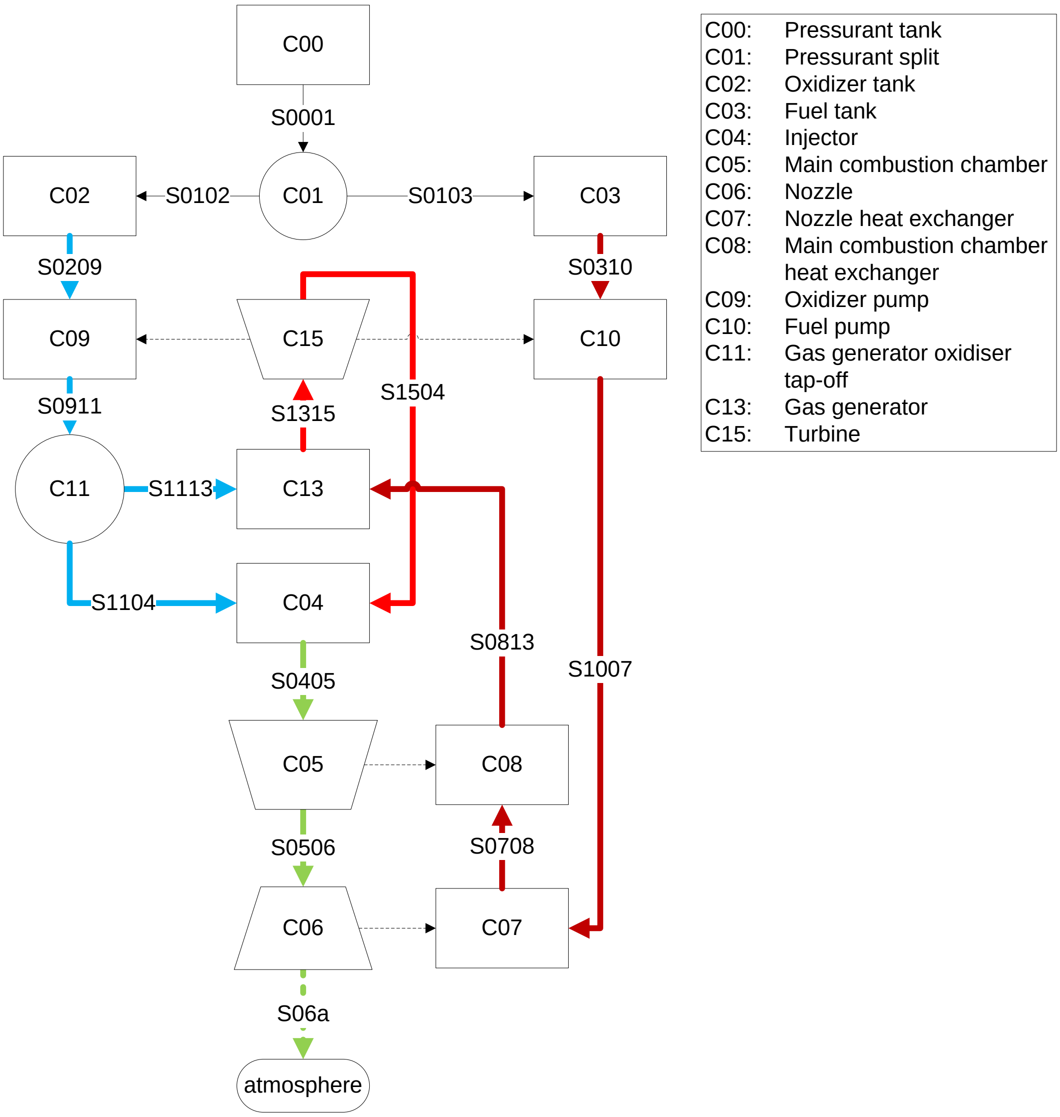


Figure A-3: Fuel rich staged combustion cycle with a single turbine with regenerative chamber and nozzle cooling

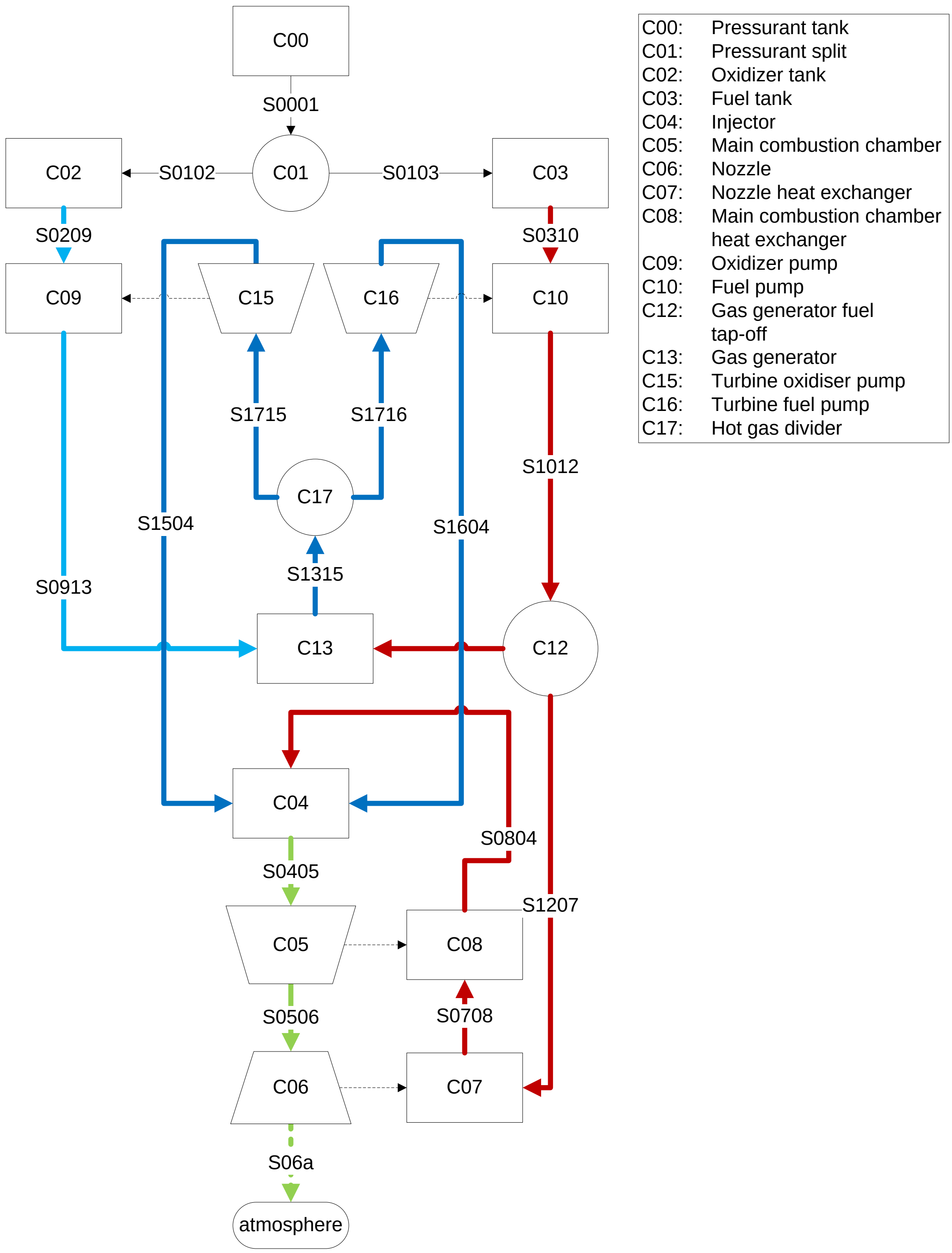
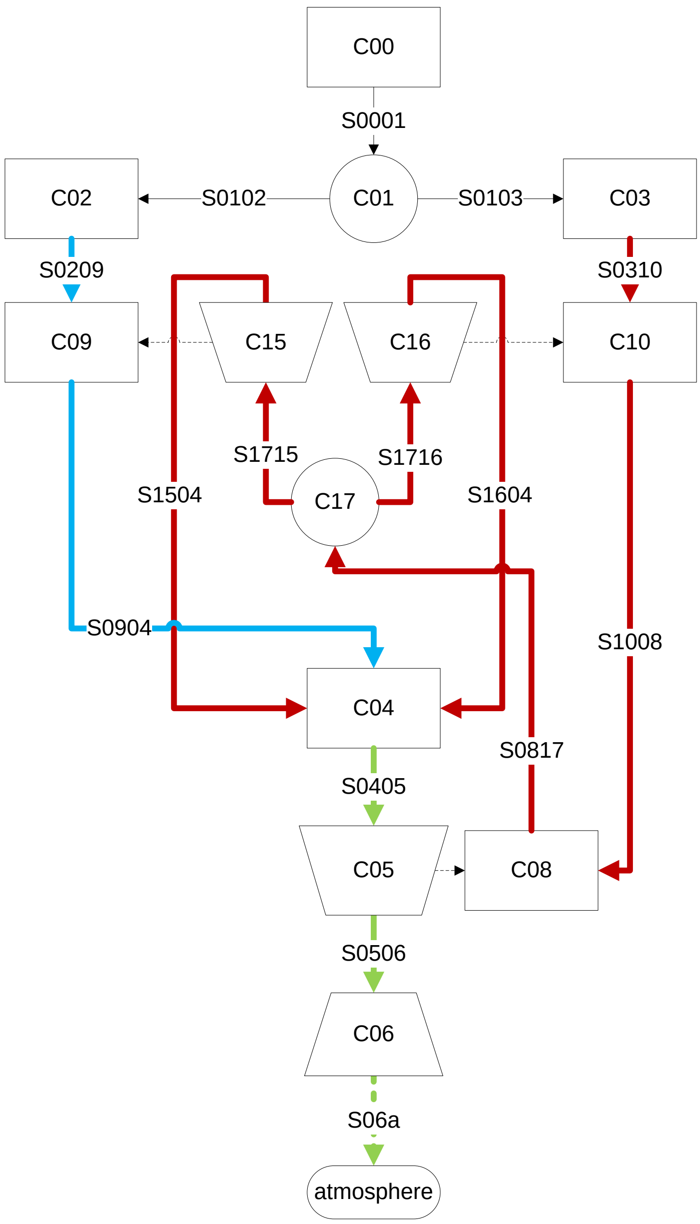


Figure A-4: Oxygen rich staged combustion cycle with double turbines with regenerative chamber and nozzle cooling



C00:	Pressurant tank
C01:	Pressurant split
C02:	Oxidizer tank
C03:	Fuel tank
C04:	Injector
C05:	Main combustion chamber
C06:	Nozzle
C08:	Main combustion chamber heat exchanger
C09:	Oxidizer pump
C10:	Fuel pump
C15:	Turbine oxidiser pump
C16:	Turbine fuel pump
C17:	Hot gas divider

Figure A-5: Closed expander cycle with double turbines with regenerative chamber cooling only

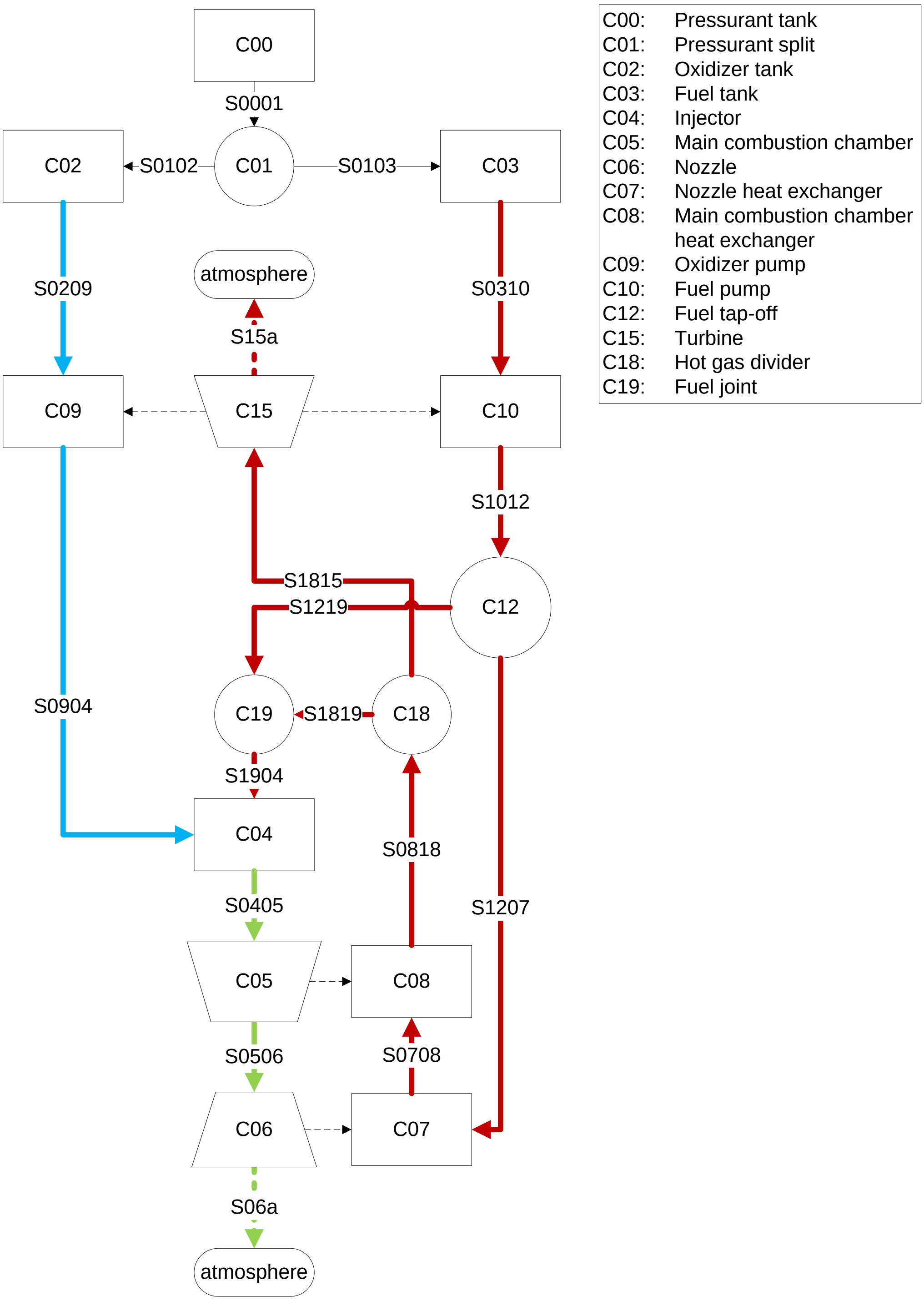


Figure A-6: Bleed expander cycle with a single turbine with regenerative chamber and nozzle cooling

Appendix B

Example Input and Output Files

LiRA makes use of ASCII tab delimited files to read data from or to write data to. These files have a certain structure and logic which is discussed in this appendix.

B-1 Input Files

Three type of input files exist; engine data files containing the input parameters of an engine, propellant data files containing substance properties and thermodynamic properties of pure substances and mixtures, and optimisation files containing the constraint values for optimisation.

B-1-1 Engine Data Files

Example of a pressure fed engine: Aestus.

Listing B.1: AESTUS input file

```
%type: Input file
%Engine: AESTUS
%engine cycle: pressure fed
%Propellants: N2O4-MMH
%Created by: Ruwan Ernst
%Date: 08/08/2013
%Legend:
%#   optional input, if no input value is given typical values will be used
     or a value assumption will be made
%#*  compulsary input
%#** compulsary input under certain condition(s);

1*  engine cycle (1: pressure fed, 2: gas generator, 3: staged combustion,
    4: closed expander cycle, 5: bleed expander cycle) [-] 1
```

```
2*  oxidizer (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]  3
3*  fuel (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]  4
4*  nozzle exit diameter [m]  1.315
5*  nozzle arearatio (Ae/At) [-]  84
6*  atmospheric pressure [Pa] 0
7*  burn time [s] 1000
8*  pressure main combustion chamber [Pa] 11e5
9 mixture ratio main combustion chamber (O/F) [-] 1.9
10  nozzle cooling (1: none, 2: regenerative):  1
11  chamber cooling (1: none, 2: regenerative): 1
12  pressurant (1: He, 2: N2) [-] 1
13  pressurant initial temperature [K]  300
14  pressurant initial pressure [Pa]  400e5
15  oxidizer initial temperature [K]  300
16  fuel initial temperature [K]  300
17  combustion chamber wall material [-]
18  nozzle wall material [-]
19  engine throttled (1: yes, 2: no) [-]
```

Example of a turbo-pump fed engine with a single turbine: HM7B.

Listing B.2: HM7B input file

```
%type: Input file
%Engine: HM7B
%engine cycle: gas generator
%Propellants: LOX-LH2
%Created by: Ruwan Ernst
%Date: 03/10/2013
%Legend:
%#   optional input, if no input value is given typical values will be used
     or a value assumption will be made
%#*  compulsary input
%#** compulsary input under certain condition(s)

1*  engine cycle (1: pressure fed, 2: gas generator, 3: staged combustion,
    4: closed expander cycle, 5: bleed expander cycle) [-] 2
2*  oxidizer (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]  1
3*  fuel (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]  2
4*  nozzle exit diameter [m]  0.992
5*  nozzle arearatio (Ae/At) [-]  82.9
6*  atmospheric pressure [Pa] 0
7*  burn time [s] 970
8*  pressure main combustion chamber [Pa] 3.6e6
9 mixture ratio main combustion chamber (O/F) [-] 4.565
10  nozzle cooling (1: none, 2: regenerative):  1
11  chamber cooling (1: none, 2: regenerative): 2
12  pressurant (1: He, 2: N2) [-] 1
13  pressurant initial temperature [K]  85
14  pressurant initial pressure [Pa]  226e5
15  oxidizer initial temperature [K]  90.17
16  fuel initial temperature [K]  20.27
17  combustion chamber wall material [-]
18  nozzle wall material [-]
```

```
19  engine throttled (1: yes, 2: no) [-]
20  Maximum Expected Operating Pressure oxidizer tank [Pa]  2.06e5
21  Maximum Expected Operating Pressure fuel tank [Pa]  3e5
22  oxidizer pump efficiency [-]  0.73
23  fuel pump efficiency [-]  0.60
24  number of turbines [-]  1
25  turbine efficiency [-]  0.45
26  turbine pressure ratio [-]  16.7
27  turbine mechanical efficiency [-] 0.97
28  maximum turbine inlet temparature [K] 860
29  mixturetype gas generator (1: fuel rich, 2: oxygen rich) [-]: 1
```

Example of a turbo-pump fed engine with two turbines: Vulcain.

Listing B.3: Vulcain input file

```
%type: Input file
%Engine: VULCAIN
%engine cycle: gas generator
%Propellants: LOX-LH2
%Created by: Ruwan Ernst
%Date: 03/10/2013
%Legend:
%#   optional input, if no input value is given typical values will be used
     or a value assumption will be made
%#*  compulsary input
%#** compulsary input under certain condition(s)

1*  engine cycle (1: pressure fed, 2: gas generator, 3: staged combustion,
    4: closed expander cycle, 5: bleed expander cycle) [-] 2
2*  oxidizer (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]  1
3*  fuel (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]  2
4*  nozzle exit diameter [m]  1.76
5*  nozzle arearatio (Ae/At) [-]  45.0
6*  atmospheric pressure [Pa] 0
7*  burn time [s] 600
8*  pressure main combustion chamber [Pa] 100e5
9 mixture ratio main combustion chamber (O/F) [-] 5.1
10  nozzle cooling (1: none, 2: regenerative):  2
11  chamber cooling (1: none, 2: regenerative): 2
12  pressurant (1: He, 2: N2) [-] 1
13  pressurant initial temperature [K]  300
14  pressurant initial pressure [Pa]  405.3e5
15  oxidizer initial temperature [K]  90.17
16  fuel initial temperature [K]  20.27
17  combustion chamber wall material [-]
18  nozzle wall material [-]
19  engine throttled (1: yes, 2: no) [-]
20  Maximum Expected Operating Pressure oxidizer tank [Pa]  3.55e5
21  Maximum Expected Operating Pressure fuel tank [Pa]  2.53e5
22  oxidizer pump efficiency [-]  0.76
23  fuel pump efficiency [-]  0.73
24  number of turbines [-]  2
25  oxidizer pump turbine efficiency [-]  0.27
```

```
26  oxidizer pump turbine pressure ratio [-]  13.6
27  oxidizer pump turbine mechanical efficiency [-]
28  maximum oxidizer pump turbine inlet temperature [K] 871
29  fuel pump turbine efficiency [-]  0.59
30  fuel pump turbine pressure ratio [-]  17.0
31  fuel pump turbine mechanical efficiency [-]
32  maximum fuel pump turbine inlet temperature [K] 871
33  mixturetype gas generator (1: fuel rich, 2: oxygen rich) [-]: 1
```

B-1-2 Propellant Property Files

Pure substances.

The data tables for pure substances were created using NIST Chemistry webbook and NASA CEA2. The tables are two dimensional yielding either density, specific heat capacity, viscosity or conductivity for a given fuel or oxidiser at a given pressure and temperature combination. An example for the specific heat capacity of RP1 can be seen in listing B.4. The pressure increases vertically downwards, while the temperature increases horizontally from left to right.

Listing B.4: RP1 specific heat capacity data table

```
% This is a heat capacity (KJ/kgK) table for RP1 at several temperture (K) and pressure (bar) combinations
%
% The data was calculated with NASA's CEA online tool (http://www.grc.nasa.gov/WWW/CEAWeb/)

     280 300 320 340 360 380 400 420 440 460 480 500 525 550 575 600 625 650 675 700 725 750 775 800 825 850 875 900 950 1000  1050  1100  1150 1200

0.5    1.5142   1.5662   1.6241   1.6893   1.7640   1.8514   1.9556   2.0819   2.2363   2.4259   2.6585   2.9421   3.3813   3.9293   4.6005   5.4049   6.3448   7.4094   8.5667   9.7556   10.880   11.813   12.4183  12.5907  12.2986  11.6029  10.6369  9.5575   7.5453   6.0837   5.1648   4.6257   4.3189   4.1480
1    1.5138   1.5651   1.6216   1.6840   1.7539   1.8332   1.9248   2.0322   2.1597   2.3121   2.4947   2.7134   3.0464   3.4564   3.9543   4.5491   5.2464   6.0463   6.9400   7.9058   8.9042   9.8744   10.7351  11.3938  11.7650  11.7954  11.4838  10.8851  9.2148   7.5340   6.2343   5.3588   4.8084   4.4739
10     1.5131   1.5633   1.6173   1.6753   1.7371   1.8031   1.8739   1.9503   2.0333   2.1241   2.2244   2.3357   2.4930   2.6738   2.8816   3.1198   3.3913   3.6985   4.0429   4.4252   4.8449   5.2997   5.7856   6.2958   6.8207   7.3474   7.8596   8.3379   9.1069   9.4958   9.4213   8.9330   8.1878   7.3680
20     1.5130   1.5630   1.6168   1.6741   1.7348   1.7991   1.8670   1.9392   2.0161   2.0987   2.1878   2.2846   2.4180   2.5677   2.7360   2.9254   3.1378   3.3751   3.6386   3.9290   4.2465   4.5906   4.9596   5.3508   5.7603   6.1825   6.6101   7.0340   7.8260   8.4585   8.8328   8.8900   8.6387   8.1548
30     1.5129   1.5629   1.6165   1.6736   1.7338   1.7973   1.8640   1.9343   2.0086   2.0874   2.1716   2.2619   2.3848   2.5207   2.6715   2.8392   3.0255   3.2317   3.4590   3.7083   3.9797   4.2730   4.5873   4.9211   5.2718   5.6361   6.0093   6.3860   7.1204   7.7717   8.2626   8.5282   8.5364   8.3042
40     1.5129   1.5628   1.6164   1.6733   1.7332   1.7962   1.8622   1.9314   2.0041   2.0807   2.1619   2.2484   2.3651   2.4927   2.6331   2.7879   2.9585
```

```
      3.1462   3.3519   3.5765   3.8202   4.0828   4.3639   4.6623   4.9762   5.3031
        5.6399   5.9824   6.6636   7.2967   7.8209   8.1781   8.3265   8.2572
50       1.5129   1.5628   1.6163   1.6730   1.7328   1.7955   1.8610   1.9294
    2.0010   2.0761   2.1554   2.2392   2.3516   2.4736   2.6069   2.7528   2.9128
      3.0878   3.2788   3.4865   3.7112   3.9528   4.2109   4.4847   4.7728   5.0732
        5.3835   5.7004   6.3378   6.9460   7.4756   7.8763   8.1057   8.1434
60       1.5129   1.5628   1.6162   1.6729   1.7325   1.7949   1.8600   1.9279
    1.9987   2.0728   2.1505   2.2324   2.3416   2.4595   2.5875   2.7270   2.8790
      3.0447   3.2249   3.4201   3.6307   3.8567   4.0978   4.3532   4.6219   4.9023
        5.1923   5.4892   6.0906   6.6741   7.1985   7.6200   7.8985   8.0088
70       1.5129   1.5627   1.6161   1.6728   1.7323   1.7945   1.8593   1.9268
    1.9969   2.0701   2.1467   2.2271   2.3339   2.4486   2.5725   2.7069   2.8528
      3.0112   3.1829   3.3684   3.5681   3.7819   4.0097   4.2508   4.5043   4.7688
        5.0426   5.3234   5.8949   6.4556   6.9706   7.4013   7.7105   7.8714
80       1.5129   1.5627   1.6161   1.6727   1.7321   1.7942   1.8588   1.9258
    1.9955   2.0680   2.1437   2.2229   2.3276   2.4398   2.5604   2.6907   2.8317
      2.9842   3.1491   3.3268   3.5176   3.7217   3.9387   4.1681   4.4092   4.6608
        4.9213   5.1888   5.7349   6.2752   6.7791   7.2126   7.5413   7.7384
90       1.5129   1.5627   1.6161   1.6726   1.7320   1.7939   1.8583   1.9251
    1.9943   2.0663   2.1412   2.2194   2.3225   2.4324   2.5503   2.6773   2.8142
      2.9619   3.1211   3.2923   3.4758   3.6717   3.8797   4.0995   4.3303   4.5711
        4.8204   5.0766   5.6009   6.1229   6.6155   7.0481   7.3893   7.6126
100      1.5129   1.5627   1.6160   1.6725   1.7318   1.7937   1.8579   1.9244
    1.9934   2.0648   2.1390   2.2164   2.3181   2.4263   2.5419   2.6659   2.7994
      2.9430   3.0974   3.2631   3.4404   3.6294   3.8299   4.0415   4.2635   4.4950
        4.7348   4.9813   5.4867   5.9923   6.4736   6.9033   7.2522   7.4950
110      1.5128   1.5627   1.6160   1.6725   1.7317   1.7935   1.8575   1.9239
    1.9925   2.0635   2.1372   2.2138   2.3144   2.4210   2.5346   2.6562   2.7866
      2.9267   3.0770   3.2380   3.4100   3.5930   3.7870   3.9915   4.2059   4.4295
        4.6610   4.8991   5.3878   5.8785   6.3491   6.7746   7.1282   7.3854
120      1.5128   1.5627   1.6160   1.6724   1.7316   1.7933   1.8572   1.9234
    1.9918   2.0624   2.1356   2.2116   2.3111   2.4163   2.5282   2.6477   2.7755
      2.9125   3.0592   3.2161   3.3834   3.5613   3.7495   3.9479   4.1557   4.3723
        4.5965   4.8271   5.3010   5.7783   6.2387   6.6594   7.0154   7.2834
130      1.5128   1.5626   1.6159   1.6724   1.7315   1.7931   1.8570   1.9230
    1.9911   2.0614   2.1342   2.2096   2.3082   2.4122   2.5226   2.6401   2.7657
      2.9000   3.0436   3.1968   3.3600   3.5333   3.7165   3.9093   4.1113   4.3217
        4.5395   4.7635   5.2241   5.6892   6.1400   6.5555   6.9124   7.1885
140      1.5128   1.5626   1.6159   1.6723   1.7314   1.7930   1.8567   1.9226
    1.9905   2.0606   2.1329   2.2079   2.3056   2.4086   2.5176   2.6335   2.7570
      2.8889   3.0296   3.1796   3.3391   3.5083   3.6870   3.8750   4.0718   4.2766
        4.4886   4.7067   5.1554   5.6092   6.0510   6.4612   6.8178   7.1001
150      1.5128   1.5626   1.6159   1.6723   1.7314   1.7929   1.8565   1.9223
    1.9900   2.0598   2.1318   2.2063   2.3033   2.4053   2.5131   2.6275   2.7492
      2.8789   3.0170   3.1641   3.3204   3.4859   3.6606   3.8442   4.0362   4.2361
        4.4429   4.6556   5.0934   5.5370   5.9703   6.3751   6.7308   7.0175
160      1.5128   1.5626   1.6159   1.6723   1.7313   1.7928   1.8563   1.9219
    1.9895   2.0591   2.1308   2.2049   2.3012   2.4024   2.5090   2.6220   2.7421
      2.8698   3.0057   3.1502   3.3034   3.4656   3.6367   3.8163   4.0041   4.1994
        4.4014   4.6093   5.0372   5.4713   5.8967   6.2961   6.6503   6.9403
170      1.5128   1.5626   1.6159   1.6722   1.7313   1.7927   1.8562   1.9217
    1.9891   2.0584   2.1299   2.2036   2.2993   2.3997   2.5053   2.6171   2.7357
      2.8616   2.9954   3.1374   3.2880   3.4472   3.6149   3.7909   3.9748   4.1660
```

```
      4.3637  4.5670  4.9859  5.4113  5.8291  6.2233  6.5756  6.8679
200   1.5128  1.5626  1.6158  1.6722  1.7311  1.7924  1.8557  1.921 1.988
    2.0568  2.1275  2.2003  2.2945  2.3929  2.496 2.6046  2.7193  2.8407
    2.9692  3.1052  3.2489  3.4004  3.5596  3.7264  3.9004  4.0811  4.2678
      4.4598  4.8552  5.2579  5.6556  6.0350  6.3803  6.6757
300   1.5128  1.5626  1.6158  1.672 1.7308  1.7918  1.8548  1.9194  1.9856
      2.0533  2.1225  2.1932  2.2841  2.3781  2.4757  2.5775  2.6839
    2.7955  2.9125  3.0353  3.1641  3.2989  3.4398  3.5866  3.7391  3.8969
      4.0594  4.2262  4.5696  4.9204  5.2702  5.6101  5.9295  6.2175
400   1.5128  1.5626  1.6157  1.6719  1.7306  1.7915  1.8542  1.9185
    1.9842  2.0512  2.1195  2.189 2.2779  2.3693  2.4636  2.5613  2.6629
    2.7685  2.8787  2.9937  3.1136  3.2385  3.3684  3.5033  3.6429  3.7869
      3.935 4.0866  4.3982  4.7164  5.0350  5.3470  5.6446  5.9193
500   1.5128  1.5625  1.6157  1.6718  1.7305  1.7913  1.8539  1.9179
    1.9833  2.0498  2.1174  2.1862  2.2737  2.3634  2.4554  2.5504  2.6485
      2.7502  2.8557  2.9653  3.0792  3.1973  3.3198  3.4465  3.5773
    3.7119  3.8499  3.9911  4.2807  4.5763  4.8725  5.1639  5.4440  5.7061
600   1.5128  1.5625  1.6157  1.6718  1.7304  1.7911  1.8536  1.9175
    1.9826  2.0488  2.1159  2.1841  2.2706  2.359 2.4494  2.5423  2.638
    2.7367  2.8388  2.9444  3.0538  3.167 3.2839  3.4046  3.5288  3.6565
    3.7872  3.9206  4.1939  4.4724  4.7517  5.0271  5.2931  5.5441
700   1.5128  1.5625  1.6157  1.6718  1.7304  1.7910  1.8534  1.9171
    1.9821  2.0480  2.1148  2.1824  2.2682  2.3556  2.4447  2.5360  2.6298
     2.7262  2.8257  2.9282  3.0341  3.1434  3.2560  3.3720  3.4912  3.6134
      3.7384  3.8658  4.1263  4.3915  4.6573  4.9198  5.1743  5.4156
```

Thermodynamic data mixtures.

For mixtures the data tables were created using only NASA CEA. The tables are two dimensional yielding either combustion temperature, molar mass, density, ratio of specific heats, specific heat capacity, viscosity or conductivity for a given fuel and oxidiser combination at a given pressure and mixture ratio combination. An example for the specific heat capacity of N2O4-MMH can be seen in listing B.5. The pressure increases vertically downwards, while the mixture ratio increases horizontally from left to right.

Listing B.5: N2O4-MMH specific heat capacity data table

```
% This is a specific heat capacity (kJ/kgK) table for mixtures of CH6N2 and
    N2O4 at various oxidizer to fuel mass ratios and various pressures (
   bar)
% Both proepllants were assumed to be stored at 298.15 Kelvin
% The data was calculated with NASA's CEA online tool (http://www.grc.nasa.
   gov/WWW/CEAWeb/)

     0.5  1  1.5  2  2.5  3  3.5  4  4.5  5  5.5  6  6.5  7  7.5  8  8.5  9  9.5  10   23   24
        25   26   29   30   34   35

0.001    2.4889   7.019  15.2711  20.429   19.9031  17.7376  15.4324  13.343
    11.5246  9.9579   8.6093   7.4463   6.4418   5.5736   4.8242   4.1795   3.6282
      3.1611   2.7699   2.4471   1.2  1.1903   1.1812   1.1727   1.1501   1.1433
    1.1192   1.1138
0.01     2.4845   5.0416   11.2116  15.5793  15.2924  13.5786  11.7464  10.0934
    8.6619   7.4353   6.3869   5.4915   4.7284   4.0806   3.5343   3.0779   2.7012
```

```
   2.3948  2.1494  1.9558  1.1998  1.1902  1.1812  1.1726  1.1501
  1.1433  1.1192  1.1138
0.1   2.5025  3.6784  7.9248  11.6045 11.5529 10.2278 8.7967  7.5127
  6.4092  5.4735  4.6852  4.0252  3.477 3.0262  2.6599  2.3663  2.1339
  1.9522  1.8112  1.7022  1.1997  1.1902  1.1811  1.1726  1.1501  1.1433
   1.1192  1.1138
1   2.7148  2.9041  5.4454  8.4586  8.6353  7.63  6.5243  5.5421  4.7123
  4.0248  3.4629  3.0091  2.6471  2.3616  2.1385  1.9654  1.8314  1.7274
   1.6462  1.5821  1.1997  1.1901  1.1811  1.1726  1.1501  1.1433
  1.1193  1.1138
4   3.173 2.658 4.349 6.9346  7.2438  6.3941  5.4472  4.618 3.9317  3.3773
   2.9365  2.5903  2.321 2.1127  1.9519  1.8273  1.7303  1.6538  1.5928
   1.5435  1.1996  1.1901  1.1811  1.1726  1.1501  1.1433  1.1193
  1.1138
8   3.5394  2.5777  3.9102  6.269 6.6423  5.8592  4.9821  4.2227  3.6036
  3.1116  2.7263  2.4279  2.1979  2.0209  1.8843  1.778 1.6944  1.6278
  1.574 1.5297  1.1996  1.1901  1.1812  1.1726  1.1501  1.1434  1.1193
  1.1138
12    3.7844  2.5407  3.6859  5.9078  6.3178  5.5701  4.731 4.011 3.43
  2.973 2.6185  2.3457  2.1364  1.9756  1.8511  1.7539  1.6769  1.6151
  1.5647  1.523 1.1997  1.1901  1.1812  1.1726  1.1501  1.1434  1.1193
  1.1138
16    3.9655  2.5182  3.5406  5.6638  6.0993  5.3752  4.5619  3.8691
  3.3147  2.8819  2.5483  2.2927  2.0971  1.9467  1.8301  1.7386  1.6658
   1.6071  1.5589  1.5187  1.1997  1.1901  1.1812  1.1726  1.1501
  1.1434  1.1193  1.1138
20    4.1072  2.5027  3.4357  5.4814  5.9364  5.2296  4.4358  3.7639
  3.2297  2.8152  2.4973  2.2545  2.0688  1.926 1.815 1.7277  1.6579
  1.6013  1.5547  1.5157  1.1997  1.1902  1.1812  1.1726  1.1501  1.1434
   1.1193  1.1138
24    4.2224  2.4912  3.3549  5.3368  5.8074  5.1141  4.3359  3.6808
  3.1631  2.7633  2.4578  2.225 2.0471  1.9102  1.8035  1.7193  1.6519
  1.5969  1.5515  1.5133  1.1997  1.1902  1.1812  1.1726  1.1501  1.1434
   1.1193  1.1138
28    4.3187  2.4821  3.2898  5.2175  5.7011  5.0189  4.2537  3.6127
  3.1087  2.7211  2.4259  2.2013  2.0297  1.8975  1.7943  1.7127  1.647
  1.5934  1.5489  1.5114  1.1997  1.1902  1.1812  1.1726  1.1501  1.1434
   1.1193  1.1139
32    4.4007  2.4748  3.2359  5.1164  5.6111  4.9383  4.184 3.5553  3.063
  2.6858  2.3993  2.1816  2.0152  1.8869  1.7867  1.7071  1.643 1.5905
  1.5468  1.5099  1.1997  1.1902  1.1812  1.1727  1.1501  1.1434  1.1193
   1.1139
36    4.4718  2.4687  3.1902  5.029 5.5334  4.8684  4.1239  3.5058  3.0237
   2.6557  2.3766  2.1648  2.003 1.878 1.7802  1.7025  1.6396  1.588
  1.545 1.5086  1.1997  1.1902  1.1812  1.1727  1.1501  1.1434  1.1193
  1.1139
40    4.534 2.4635  3.1507  4.9521  5.465 4.807 4.071 3.4624  2.9895
  2.6295  2.357 2.1503  1.9924  1.8704  1.7747  1.6984  1.6367  1.5859
  1.5434  1.5074  1.1997  1.1902  1.1812  1.1727  1.1501  1.1434  1.1193
   1.1139
44    4.5892  2.4591  3.1161  4.8836  5.4042  4.7523  4.0239  3.4239
  2.9592  2.6063  2.3397  2.1376  1.9831  1.8636  1.7698  1.6949  1.6341
   1.584 1.542 1.5064  1.1997  1.1902  1.1812  1.1727  1.1501  1.1434
```

```
      1.1193  1.1139
48     4.6385  2.4552  3.0854  4.8219  5.3494  4.7031  3.9816  3.3893
      2.9321  2.5857  2.3243  2.1263  1.9749  1.8577  1.7655  1.6918  1.6318
        1.5823  1.5408  1.5055  1.1997  1.1902  1.1812  1.1727  1.1501
      1.1434  1.1193  1.1139
52     4.6829  2.4518  3.058 4.766 5.2998  4.6584  3.9432  3.3581  2.9077
      2.5671  2.3105  2.1162  1.9675  1.8523  1.7616  1.6889  1.6298  1.5809
        1.5397  1.5047  1.1997  1.1902  1.1812  1.1727  1.1501  1.1434
      1.1193  1.1139
56     4.7231  2.4487  3.0332  4.7148  5.2544  4.6174  3.9081  3.3295
      2.8854  2.5503  2.298 2.107 1.9609  1.8475  1.7581  1.6864  1.628
      1.5795  1.5388  1.504 1.1997  1.1902  1.1812  1.1727  1.1501  1.1434
      1.1193  1.1139
60     4.7597  2.446 3.0107  4.6677  5.2126  4.5797  3.8758  3.3034  2.865
      2.5349  2.2866  2.0987  1.9548  1.8431  1.7549  1.6841  1.6263  1.5783
        1.5379  1.5033  1.1997  1.1902  1.1812  1.1727  1.1501  1.1434
      1.1193  1.1139
64     4.7932  2.4435  2.9901  4.6242  5.1739  4.5449  3.8459  3.2792
      2.8463  2.5207  2.2761  2.091 1.9493  1.8391  1.752 1.682 1.6248
      1.5772  1.5371  1.5027  1.1997  1.1902  1.1812  1.1727  1.1501  1.1434
        1.1193  1.1139
100    5.0032  2.4283  2.8598  4.3354  4.9175  4.3129  3.6482  3.1206
      2.7242  2.4293  2.2089  2.0421  1.9139  1.8135  1.7335  1.6686  1.615
      1.57  1.5318  1.4989  1.1997  1.1902  1.1812  1.1727  1.1502  1.1434
      1.1193  1.1139
150    5.1569  2.4175  2.7583  4.0916  4.7005  4.1158  3.4816  2.9889
      2.6244  2.3556  2.1552  2.0033  1.8858  1.7933  1.7188  1.6579  1.6072
        1.5644  1.5277  1.4958  1.1998  1.1903  1.1813  1.1727  1.1502
      1.1435  1.1193  1.1139
200    5.2422  2.4113  2.6951  3.9293  4.5553  3.9834  3.3707  2.9024
      2.5597  2.3083  2.1209  1.9786  1.8681  1.7804  1.7096  1.6512  1.6023
        1.5608  1.525 1.4939  1.1998  1.1903  1.1813  1.1728  1.1502  1.1435
        1.1194  1.1139
250    5.2941  2.4074  2.6508  3.8094  4.4474  3.8849  3.2887  2.8391
      2.5128  2.2742  2.0964  1.961 1.8554  1.7713  1.7029  1.6464  1.5988
      1.5582  1.5231  1.4925  1.1998  1.1903  1.1813  1.1728  1.1502  1.1435
        1.1194  1.1139
300    5.3271  2.4048  2.6174  3.7152  4.3623  3.807 3.2243  2.7899  2.4766
        2.248 2.0776  1.9475  1.8457  1.7643  1.6979  1.6427  1.5961  1.5562
        1.5217  1.4914  1.1999  1.1903  1.1813  1.1728  1.1502  1.1435
      1.1194  1.1139
350    5.3484  2.4031  2.5911  3.6384  4.2925  3.7429  3.1717  2.75  2.4473
        2.227 2.0625  1.9367  1.8379  1.7587  1.6938  1.6397  1.5939  1.5546
        1.5205  1.4906  1.1999  1.1904  1.1814  1.1728  1.1503  1.1435
      1.1194  1.114
400    5.362 2.402 2.5696  3.5738  4.2334  3.6887  3.1274  2.7166  2.423
      2.2095  2.0501  1.9278  1.8315  1.7541  1.6905  1.6373  1.5922  1.5533
        1.5196  1.4899  1.1999  1.1904  1.1814  1.1728  1.1503  1.1435
      1.1194  1.114
```

B-1-3 Optimisation

The optimisation routine requires the user to provide the constraints in a dedicated constraint file. This file contains the minimal and maximal values for delta V, engine vacuum thrust, total wet mass, total diameter, total length, total volume and L/d ratio of the tanks. In case no value is assigned to the minimum or maximum bound, minus infinity for the minimum bound and plus infinity for the maximum bound respectively are automatically assumed. As example constraint file, the file used for the optimising of the engine cycle for use in the Ariane V ME like upperstage is given in listing B.6.

Listing B.6: Constraint file for Ariane V ME upperstage like test case

```
%type: Input file
%what:constraints for optimisation
%Project: Ariane 5 LiRA Uppertge
%Create by:
%Date:
%
%if boudary value is left blank minus or plus infinity will be assumed for
    min and max bound respectively
%NOTE: all bound values are required in SI units
%
%Parameter  unit  Min Max
%
Delta V [m/s]
F/W ratio [-]
Engine thrust [N]
Total wet mass  [kg]  0
Total diameter  [m] 0 5.4
Total length  [m] 0
Total volume  [m3]  0
L/d tanks [-] 0 3
```

B-2 Output Files

When conducting optimisation or sensitivity and uncertainty analysis, the most important results are stored in text files.

B-2-1 Optimisation

The optimisation output file contains the input data for the optimised engine cycles, the accompanying total wet mass, vacuum thrust, engine overall length, engine overall diameter, volume oxidiser tank, volume fuel tank, volume pressurant tank, delta v and engine volume. Additionally in case a maximal tank diameter or length is specified also the length of the tanks, the L/d ratio and the length of the total propulsion system in case the tanks are cylinders with hemispherical ends is shown. A negative value indicates that if the diameter of the tanks is taken equal to the maximal diameter, the amount of volume that needs to be stored in the tank is insufficient to yield a positive tank height. Hence another tank shape should be chosen. An example of an optimisation output file is shown in listing B.7.

Listing B.7: Optimisation output file for Ariane V ME upperstage like test case

```
%Optimal solutions for Ariane 5 upper stage

  pressure fed  pressure fed  gas generator staged combustion closed expander cycle bleed expander cycle
requirements
Delta V [m/s] 3.40e+03  3.40e+03  3.40e+03  3.40e+03  3.40e+03  3.40e+03
thrust-to-weight ratio [-]  2.45e-01  2.45e-01  2.45e-01  2.45e-01  2.45e-01  2.45e-01
payload mass [kg] 8.00e+03  8.00e+03  8.00e+03  8.00e+03  8.00e+03  8.00e+03

fixed input
oxidiser  N2O4  LOX LOX LOX LOX LOX
fuel  MMH LH2 LH2 LH2 LH2 LH2
chamber cooling no cooling  no cooling  no cooling  no cooling  regenerative cooling  regenerative cooling
nozzle cooling  no cooling  no cooling  no cooling  no cooling  regenerative cooling  regenerative cooling
atmospheric pressure [pa] 0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00  0.000000e+00

optimised input
main combustion chamber pressure [Pa] 1.553355e+06  6.291099e+05  4.069416e+06  8.211560e+06  6.016197e+06  2.394317e+06
main combustion chamber mixture ratio [-] 2.388112e+00  6.566558e+00  4.193876e+00  3.941407e+00  3.796658e+00  5.283360e+00
nozzle exit diameter [m]  2.712823e+00  3.318462e+00  1.244346e+00  1.059237e+00  1.118024e+00  1.807178e+00
nozzle area ratio [-] 1.951476e+02  1.757803e+02  1.999338e+02  2.969106e+02  2.374054e+02  2.523131e+02

output
thrust [N]  8.981314e+04  6.049677e+04  4.753587e+04  4.733133e+04  4.775081e+04  4.784564e+04
Isp [s] 3.406175e+02  4.435454e+02  4.782805e+02  4.860109e+02  4.808165e+02  4.746157e+02
Delta V [m/s] 3.435985e+03  3.394104e+03  3.420562e+03  3.390967e+03  3.391034e+03  3.427545e+03
thrust to weight ratio [-]  2.533764e-01  2.389821e-01  2.432584e-01  2.467459e-01  2.458993e-01  2.487154e-01
burn time [s] 8.600000e+02  1.000000e+03  9.900000e+02  1.000000e+03  1.000000e+03  9.900000e+02
engine oxidiser mass flow [kg/s]  1.895174e+01  1.207016e+01  8.313915e+00  7.921049e+00  8.015735e+00  8.643663e+00
engine fuel mass flow [kg/s]  7.935871e+00  1.838125e+00  2.079113e+00  2.009701e+00  2.111261e+00  1.659356e+00
engine total mass flow [kg/s] 2.688762e+01  1.390828e+01  1.039303e+01  9.930749e+00  1.012700e+01  1.030302e+01
engine dry mass [kg]  1.365066e+02  1.063192e+02  1.141776e+02  1.251659e+02  1.206880e+02  1.087642e+02
pressurant tank mass [kg] 6.451900e+02  4.872629e+02  1.785279e+02  1.738126e+02  1.812761e+02  1.510733e+02
```

```
oxidiser tank mass [kg] 6.814334e+02 2.667771e+02 6.842241e+01 6.584765e+01 6.663478e+01 7.113619e+01
fuel tank mass [kg] 4.822118e+02 6.532349e+02 2.751247e+02 2.686257e+02 2.822007e+02 2.195791e+02
total dry mass [kg] 4.921715e+03 3.829393e+03 1.609719e+03 1.602633e+03 1.646523e+03 1.392899e+03
pressurant mass [kg] 1.003440e+02 7.578221e+01 2.776578e+01 2.703244e+01 2.819320e+01 2.349587e+01
oxidiser mass [kg] 1.629850e+04 1.207016e+04 8.230776e+03 7.921049e+03 8.015735e+03 8.557226e+03
fuel mass [kg] 6.824849e+03 1.838125e+03 2.058322e+03 2.009701e+03 2.111261e+03 1.642763e+03
propellant mass [kg] 2.322369e+04 1.398406e+04 1.031686e+04 9.957782e+03 1.015519e+04 1.022348e+04
total wet mass [kg] 2.814541e+04 1.781346e+04 1.192658e+04 1.156041e+04 1.180171e+04 1.161638e+04
payload mass [kg] 8.000000e+03 8.000000e+03 8.000000e+03 8.000000e+03 8.000000e+03 8.000000e+03
total dry mass incl. payload [kg] 1.292171e+04 1.182939e+04 9.609719e+03 9.602633e+03 9.646523e+03 9.392899e+03
total wet mass incl. payload [kg] 3.614541e+04 2.581346e+04 1.992658e+04 1.956041e+04 1.980171e+04 1.961638e+04
engine overall length [m] 3.839127e+00 3.249536e+00 1.835151e+00 1.873441e+00 1.854705e+00 1.861869e+00
engine overall diameter [m] 2.362449e+00 2.031953e+00 1.196044e+00 1.284845e+00 1.235929e+00 1.250514e+00
volume oxidizer tank [m3] 1.157301e+01 1.110420e+01 7.572080e+00 7.287140e+00 7.374249e+00 7.872406e+00
volume fuel tank [m3] 8.189566e+00 2.718993e+01 3.044713e+01 2.972791e+01 3.123021e+01 2.430009e+01
volume pressurant tank [m3] 1.967830e+00 1.486152e+00 5.445100e-01 5.301285e-01 5.528920e-01 4.607735e-01
engine volume [m3] 1.682857e+01 1.053752e+01 2.061844e+00 2.429023e+00 2.225111e+00 2.286736e+00
total volume [m3] 3.855898e+01 5.031781e+01 4.062557e+01 3.997421e+01 4.138247e+01 3.492001e+01
nozzle throat diameter [m] 1.941958e-01 2.502947e-01 8.800310e-02 6.147240e-02 7.256144e-02 1.137709e-01
```

B-2-2 Sensitivity and Uncertainty

One-at-the-time.

The OAT sensitivity analysis gives the results of the first order sensitivity analysis method which are sensitivity of the considered performance output parameter to the considered input parameters expressed in percent and the resulting standard deviation of the performance parameter. Additionally also the intermediate results needed in the first order sensitivity analysis method used are shown. An example of such file is the sensitivity analysis of the knowledge parameters of the HM7B based example gas generator cycle engine shown in listing B.8.

Listing B.8: First order one-at-the-time sensitivity analysis of knowledge parameters of the optimised gas generator cycle for the Ariane V ME upperstage like test case

```
%OAT total wet mass [kg] sensitivity analysis results for test_gas_generator

input parameter X X_{low} X_{high}  output parameter I  I_{low} I_{high} deltaI/deltaX St.Dev[X] (deltaI/deltaX)^2Var[X] %

main combustion chamber pressure [Pa] 500000  1.05e+07  total wet mass [kg] 2007.77 43351.8 0.00413441  3.0303e+06  1.56963e+08 1.14032
main combustion chamber mixture ratio [-] 3 7 total wet mass [kg] 14481 15429.9 237.222 1.21212 82680.3 0.000600662
nozzle exit diameter [m]  1 5 total wet mass [kg] 14691.8 370519  88956.7 1.21212 1.16265e+10 84.4651
nozzle area ratio [-] 8 300 total wet mass [kg] 150293  4006.36 -500.982 88.4848 1.96509e+09 14.2761
atmospheric pressure [Pa] 0 101325  total wet mass [kg] 14453.5 14295.9 -0.00155566 30704.5 2272.81 1.65117e-05
burn time [s] 100 1000  total wet mass [kg] 1613.09 14896.3 14.7591 272.727 1.62022e+07 0.117707
pressurant initial pressure [Pa]  1.5e+07 3.31e+07  total wet mass [kg] 14429.4 14446.3 9.33031e-07 5.48485e+06 26.1891 1.90261e-07
MEOP oxidizer tank [Pa] 110000  340000  total wet mass [kg] 14396.8 14500.1 0.000449285 69697 980.556 7.12362e-06
MEOP fuel tank [Pa] 110000  340000  total wet mass [kg] 14248 14531.4 0.0012322 69697 7375.45 5.35817e-05
pump efficiency [-] 0.58472 0.79528 total wet mass [kg] 14520.1 14443.8 -362.61 0.064 538.567 3.91262e-06
turbine efficiency [-]  0.344825  0.723175  total wet mass [kg] 14687.8 14446.4 -637.96 0.115 5382.48 3.91031e-05
turbine mechanical efficiency [-] 0.65  0.975 total wet mass [kg] 14565.3 14453.5 -344.147  0.0984848 1148.75 8.34554e-06
turbine pressure ratio [-]  4.59  22  total wet mass [kg] 14599.8 14449 -8.66074  5.27576 2087.75 1.51673e-05
turbine inlet temperature [K] 800 1350  total wet mass [kg] 14456 14456.4 0.000589046 166.667 0.00963821  7.00204e-11

standard deviation total wet mass [kg]: 117324
```

Monte Carlo Analysis.

For Monte Carlo analysis a output files are created containing all input samples for all input parameters generated and the resulting, among others, total wet mass, total volume and vacuum thrust of those samples. As these files are very long (due to the large amount of samples) the result of an analysis of a gas generator cycle with only a three samples is given as example in B.9.

Listing B.9: Sampling bases Monte Carlo sensitivity analysis of knowledge parameters of an example gas generator cycle

```
% Monte Carlo sensitivity study output results obtained for test_gg

requirements
Delta V [m/s] 3.403400e+03
thrust-to-weight ratio [-]  2.450000e-01
payload mass [kg] 8.000000e+03
```

```

fixed input
oxidiser  LOX
fuel  LH2
chamber cooling no cooling
nozzle cooling  no cooling
atmospheric pressure [pa] 0.000000e+00

sample: 1 2 3

uncertainty parameter values generated
dry mass correction factor [-]  3.77153 2.98902 0.646929
specific impulse correction factor [-]  0.891675  0.906578  0.968705
propellant tank performance factor [-]  62002.1 19161.2 64763.2
pressurant tank performance factor [-]  150363  119535  149946

optimised input
main combustion chamber pressure [Pa] 3.385960e+06  2.436101e+06  3.103940e
    +06
main combustion chamber mixture ratio [-] 5.473431e+00  5.490024e+00
    4.080182e+00
nozzle exit diameter [m]  1.326426e+00  1.644143e+00  1.481119e+00
nozzle area ratio [-] 1.870133e+02  1.858444e+02  2.789805e+02

performance output
thrust  4.805992e+04  5.438822e+04  4.019030e+04
specific impulse  4.622659e+02  4.687383e+02  5.228391e+02
Delta V  3.417167e+03  3.433745e+03  3.436491e+03
thrust-to-weight-ratio  2.421957e-01  2.479617e-01  2.549941e-01
burn time 9.900000e+02  9.800000e+02  9.800000e+02
engine oxidiser mass flow 9.062087e+00  1.008483e+01  6.371133e+00
engine fuel mass flow 1.733996e+00  1.897635e+00  1.617069e+00
engine total mass flow  1.079608e+01  1.198246e+01  7.988202e+00

mass output
engine dry mass 1.125479e+02  1.203951e+02  9.687030e+01
pressurant tank mass  1.281925e+02  1.754132e+02  1.115055e+02
oxidiser tank mass  3.993488e+01  1.423535e+02  2.660787e+01
fuel tank mass  1.228658e+02  4.306961e+02  1.085877e+02
total dry mass  1.521967e+03  2.597035e+03  2.222662e+02
pressurant mass 2.457245e+01  2.673006e+01  2.131456e+01
oxidiser mass 8.971466e+03  9.883133e+03  6.243710e+03
fuel mass 1.716656e+03  1.859682e+03  1.584728e+03
propellant mass 1.071269e+04  1.176955e+04  7.849753e+03
total wet mass  1.223466e+04  1.436658e+04  8.072019e+03
payload mass  8.000000e+03  8.000000e+03  8.000000e+03
total dry mass incl. payload  9.521967e+03  1.059704e+04  8.222266e+03
total wet mass incl. payload  2.023466e+04  2.236658e+04  1.607202e+04

dimension output
engine overall length 1.833540e+00  1.891645e+00  1.790771e+00
engine overall diameter 1.184869e+00  1.222941e+00  1.216329e+00
volume oxidizer tank  8.253495e+00  9.092203e+00  5.744036e+00
```

```
volume fuel tank  2.539314e+01  2.750881e+01  2.344163e+01
volume pressurant tank  4.818860e-01  5.241986e-01  4.179962e-01
engine volume 2.021720e+00  2.221983e+00  2.080809e+00
total volume  3.615024e+01  3.934720e+01  3.168447e+01
```

Appendix C

Model Component Naming, Input and Output

Tables C-1, to C-4 give an overview of the naming, input and output of each component found in the engine cycles depicted in appendix A.

Table C-1: Overview of components input and output (1/4)

#	name	Input	Output
C00	Pressurant tank	- Volume oxidizer tank - Volume fuel tank - Initial pressure - Initial temperature - Final pressure - Final temperature - Pressurant choice - MEOP oxidizer tank - MEOP fuel tank	- Volume pressurant - Mass pressurant - Volume pressurant tank
C01	Pressurant split	/	/
C02	Oxidizer tank	- Oxidizer mass flow - Burn time - Oxidizer density - MEOP oxidizer tank	- Volume oxidizer tank - Mass oxidizer
C03	Fuel tank	- Fuel mass flow - Burn time - Fuel density - MEOP fuel tank	- Volume fuel tank - Mass fuel
C04	Injector	- Specific heat ratio in combustion chamber - Pressure in combustion chamber - Chamber Mach number - Molar mass oxidizer - Molar mass fuel - Mixture ratio in combustion chamber - Specific heat capacity oxidizer at injector inlet - Specific heat capacity fuel at injector inlet - Temperature oxidizer at injector inlet - Temperature fuel at injector inlet - Oxidizer mass flow to injector inlet - Fuel mass flow to injector inlet - Velocity of gases in combustion chamber - Pressure drop over combustion chamber cooling channels - Pressure drop over nozzle cooling channels - Pressure at oxidizer tank outlet - Pressure at fuel tank outlet - Pressure rise over oxidizer pump - Pressure rise over fuel pump	- Required oxidizer pressure at injector inlet - Required fuel pressure at injector inlet - Pressure after injector plate - Specific heat unignited propellant mixture - Temperature unignited propellant mixture - Molar mass unignited propellant mixture - Specific heat ratio unignited propellant mixture - Velocity gases after injector plate - Mach number after injector plate - Pressure rise over oxidizer pump - Pressure rise over fuel pump - Boolean indicating if pressure rise over pumps has been found

Table C-2: Overview of components input and output (2/4)

#	name	Input	Output
C05	Combustion chamber	- Oxidizer - Fuel - Chamber mixture ratio - Chamber pressure - Throat cross-sectional area - Chamber cross-sectional area	- Specific heat ratio hot gas - Chamber temperature - Molar mass hot gas - Density hot gas - Specific heat hot gas - Viscosity hot gas - Conductivity hot gas - Prandtl number gas flow - Chamber Mach number - Chamber velocity - Chamber total conditions (p_0, ρ_0 and T_0) - Chamber mass flow - Oxidizer mass flow at injector inlet - Fuel mass flow at injector inlet - Mass flow from nozzle cooling channels to combustion chamber cooling channels - Fuel mass flow to nozzle cooling channels inlet
C06	Nozzle	- Nozzle length - Nozzle throat diameter - Chamber pressure - Chamber mixture ratio - Chamber total conditions (p_0, ρ_0 and T_0) - Nozzle half divergence angle - Atmospheric pressure - Chamber mass flow	- Exit Mach number - Exit pressure - Exit temperature - Exit density - Exit velocity - Nozzle thrust coefficient - Nozzle characteristic velocity - Nozzle specific impulse - Nozzle thrust - Segmented nozzle length - Exit specific heat ratio - Exit molar mass - Nozzle total conditions - Exit mass flow - Exit mixture ratio - Exit viscosity - Exit Reynolds number - Nozzle efficiency - Data table containing all flow properties at each segmented interval between nozzle throat and exit

Table C-3: Overview of components input and output (3/4)

#	name	Input	Output
C07	Throat and nozzle cooling	- Nozzle cooling channels inlet temperature	- Nozzle cooling channel exit pressure
		- Nozzle cooling channels inlet pressure	- Nozzle cooling channel exit temperature
		- Total nozzle cooling channels inlet mass flow	- Fuel specific heat capacity at nozzle cooling channel exit
		- Mass flow through chamber	- Fuel density at nozzle cooling channel exit
		- Temperature at cooling channel inlet	- Total mass flow at nozzle cooling channels exit
		- Molar mass fuel at cooling channels inlet	- Molar mass of fuel at nozzle cooling channel exit
		- Data table containing all flow properties at each segmented interval between nozzle throat and exit	- Pressure loss over nozzle cooling channels inlet and exit
			- Fuel choice
			- Data table containing flow properties of the coolant at each segmented cooling channel interval between cooling channel
C08	Chamber cooling	- Combustion chamber length	- Length discretized combustion chamber element
		- Combustion chamber cooling channels inlet temperature	- Fuel mass flow to injector inlet
		- Combustion chamber cooling channels inlet pressure	- Molar mass fuel at injector inlet
		- Total massflow into the combustion chamber cooling channels	- Temperature fuel at injector inlet
		- Pressure in combustion chamber	- Fuel mass flow to injector inlet
		- Combustion chamber cross-sectional area	- Specific heat capacity fuel at injector inlet
		- Specific heat capacity gas in combustion chamber	- Density fuel at injector inlet
		- Combustion chamber diameter	- Viscosity fuel at injector inlet
		- Prandtl number gasflow in combustion chamber	- Conductivity fuel at injector inlet
		- Viscosity gas in combustion chamber	- Pressure loss over combustion chamber cooling channels
		- Combustion temperature in combustion chamber	
		- Specific heat ratio in combustion chamber	
		- Chamber mass flow	
		- Fuel choice	
		- Molar mass fuel at inlet combustion chamber cooling channels	

Table C-4: Overview of components input and output (4/4)

#	name	Input	Output
C09	Oxidizer pump	- Oxidizer mass flow through pump - Pump inlet pressure - Pump pressure rise - Pump efficiency - Oxidiser density	- Pump outlet pressure - Pump power
C10	Fuel pump	- Fuel mass flow through pump - Pump inlet pressure - Pump pressure rise - Pump efficiency - Fuel density	- Pump outlet pressure - Pump power
C11	Oxidiser tap-off	/	/
C12	Fuel tap-off	/	/
C13	Gas generator	- Mixture ratio gas generator - Pressure gas generator - Oxidizer - Fuel - Mass flow through gas generator	- Specific heat ratio gas generator - Molar mas hot gas gas generator - Specific heat hot gas gas generator - Oxidizer mass flow to gas generator - Fuel mass flow to gas generator
C14	Gas generator	- Mixture ratio gas generator - Pressure gas generator - Oxidizer - Fuel - Mass flow through gas generator	- Specific heat ratio gas generator - Molar mas hot gas gas generator - Specific heat hot gas gas generator - Oxidizer mass flow to gas generator - Fuel mass flow to gas generator
C15	Turbine	- Turbine inlet pressure - Turbine pressure ratio - Turbine efficiency - (total) Pump power - Turbine shaft mechanical efficiency - Specific heat hot gas at inlet - Turbine inlet temperature - Specific heat ratio	- Turbine outlet pressure - Turbine outlet temperature - Turbine power - Mass flow through turbine
C16	Turbine	- Turbine inlet pressure - Turbine pressure ratio - Turbine efficiency - (total) Pump power - Turbine shaft mechanical efficiency - Specific heat hot gas at inlet - Turbine inlet temperature - Specific heat ratio	- Turbine outlet pressure - Turbine outlet temperature - Turbine power - Mass flow through turbine
C17	Split hot gas	/	/
C18	Split hot gas	/	/
C19	Fuel joint	/	/

Appendix D

Engine Data

For the reader's convenience, this appendix contains engine data collected and used.

Data for the AESTUS engine in tables comes from reference [1].

Data used for VULCAIN 2 were obtained from references [2], [3], [4],[5], [6] and [7].

Data used for the AESTUS 2 engine come from references [2] and [8]

Data used for HM7B, LE-5, S-4(MA-3), LR91, H-1, HM60, J2, RS-27, F-1 in tables D-5 to D-11 were taken from Mc Huges [9].

Data used for VINCI were taken from [10],[11] and [2].

Data used for RL10A-3-A were taken from [9] and [12].

Data used for LE-7 were taken from [9], [12] and [13].

Note that Vulcain is another name for the HM60 engine and the AESTUS II engine is also designated as RS-72.

Tables D-1 and D-5 show general engine performance data: vacuum thrust (F), vacuum specific impulse (I_{sp}), main combustion chamber pressure (p_c), nozzle area ratio (A_e/A_t) and main combustion chamber mixture ratio (MR).

Tables D-2 and D-6 contain the overall length (L), nozzle exit diameter (d_e) and engine dry mass (m_{dry}).

Tables D-3 and D-7 display all combustion chamber related parameters: main combustion chamber length (L_c), main combustion chamber diameter (d_c), characteristic length (L^*)[1], main combustion chamber mass (m_c) and chamber contraction ratio (A_c/A_t).

Tables D-4 and D-8 hav the data of injector related parameters: pressure drop over the injector (injector Δp), pressure drop over the feed system (feed Δp)[2] and injector mass flow (mass flow).

[1] the combustion chamber characteristic length displayed is defined as the volume of the combustion chamber area divided by the nozzle throat area [9]

[2] the feed system pressure drop displayed is the total pressure difference between pump outlet and combustion chamber pressure

Table D-9 shows pump characteristic parameters such as mass flow (mass flow), discharge pressure (p_{out}) and pump efficiency (η_p).

Table D-10 contains important turbine related parameters like turbine pressure ratio (p_{in}/p_{out}), turbine efficiency (η_T) and required power (P_T). the '=' symbol indicates that a single turbine drives both the fuel and oxidizer pump.

Finally table D-11 has parameters related to the gas generator: mass flow through the gas generator ($\dot{m}_{gg}$), gas generator combustion temperature (T_{gg}), gas generator combustion pressure (p_{gg}) and gas generator mixture ratio (MR_{gg}).

The '−' symbol in tables indicates no data was found for this parameter.

D-1 Pressure fed engines

Table D-1: General performance parameters

Engine	F [kN]	I_{sp} [s]	p_c [MPa]	A_e/A_t [−]	MR [−]	propellant	operation point
AESTUS	27.5	324	1.77	84	1.9	N2O4-MMH	altitude
AJ10-118K	43.4	320.5	0.896	65	1.9	N2O4-Aerozine 50	-
Transtar	16.7	328	2.380	132	1.8	N2O4-MMH	-
AJ10-137	97.5	312	0.690	-	1.6	N2O4-Aerozine 50	-
Liberty-2	17.8	300	-	98	-	N2O4-MMH	-

Table D-2: Physical parameters

Engine	L [m]	d_e [m]	m_{dry} [kg]
AESTUS	2.2	1.3	111
AJ10-118K	2.7	-	124.7
Transtar	1.3	-	76
AJ10-137	4.0	-	-
Liberty-2	-	-	41

Table D-3: Combustion chamber parameters

Engine	L_c [m]	d_c [m]	L^* [m]	m_c [kg]	A_c/A_t
AESTUS	-	-	-	-	-
AJ10-118K	-	-	-	-	-
Transtar	-	-	-	-	-
AJ10-137	-	-	-	-	-
Liberty-2	-	-	-	-	-

Table D-4: Injector parameters

	mass flow [kg/s]		
Engine	fuel	ox	total
AESTUS	3.20	6.10	9.3
AJ10-118K	9.1	4.76	-
Transtar	-	-	-
AJ10-137	-	-	-
Liberty-2	-	-	-

D-2 Gas Generator Cycle Engines

Table D-5: General performance parameters

Engine	F [kN]	I_{sp} [s]	p_c [MPa]	A_e/A_t [−]	MR [−]	propellant	operation point
HM7B	62.2	445.5	3.6	82.9	4.565	LOX-LH2	altitude
LE-5	103.0	450.0	3.65	140.0	5.5	LOX-LH2	altitude
S-4(MA-3)	364.0	308.7	4.6	25.0	2.27	LOX-RP1	sea level
H-1	945.4	292.0	4.12	8.0	2.26	LOX-RP1	-
HM60	1025.0	433.5	10.0	45.0	5.1	LOX-LH2	sea level
J2	1023.0	425.0	5.4	27.5	5.5	LOX-LH2	altitude
RS-27	1043.0	301.8	4.87	12.0	2.245	LOX-RP1	sea level
F-1	7775.5	304.8	7.76	16.0	2.27	LOX-RP1	sea level
VULCAIN 2	1350	434	11.6	60	6.13	LOX-LH2	-
AESTUS 2	55.4	340	6.0	300	2.2	N2O4-MMH	-

Table D-6: Physical parameters

Engine	L [m]	d_e [m]	m_{dry} [kg]
HM7B	2.01	0.992	158.0
LE-5	2.7	1.65	255.0
S-4(MA-3)	2.41	1.22	470.4
H-1	2.67	1.24	878.2
HM60	3.1	1.76	1719.0
J2	3.38	2.05	1542.0
RS-27	3.77	1.44	1146.6
F-1	6.1	3.66	8436.8
VULCAIN 2	3.44	2.09	-
AESTUS 2	2.286	1.3	138

Table D-7: Combustion chamber parameters

Engine	L_c [m]	d_c [m]	L^* [m]	m_c [kg]	A_c/A_t
HM7B	0.283	0.180	0.68	69.0	2.78
LE-5	0.351	0.240	0.84	40.8	3.11
S-4(MA-3)	2.18	0.303	1.09	166.0	1.66
H-1	2.18	0.53	0.983	331.0	1.67
HM60	0.426	0.415	0.84	430.0	2.99
J2	0.4572	0.47	0.62	446.8	1.58
RS-27	2.34	0.52	0.99	415.0	1.62
F-1	3.35	1.02	1.22	-	-
VULCAIN 2	-	-	-	-	-
AESTUS 2	-	0.130	0.666	-	-

Table D-8: Injector parameters

	injector Δp [kPa]		feed Δp [kPa]		mass flow [kg/s]		
Engine	fuel	ox	fuel	ox	fuel	ox	total
HM7B	920	1110	1930	1400	2.26	11.64	13.9
LE-5	549	1215	2390	1540	3.24	19.5	22.74
S-4(MA-3)	490	745	2489	2241	33.8	83.1	116.9
H-1	965	1076	2980	2180	96.5	232.9	329.4
HM60	-	-	5800	3000	34.0	198.0	232.0
J2	683	1248	3220	2240	36.1	206.2	242.3
RS-27	427	793	2220	2380	102.4	244.4	346.8
F-1	641	2100	5240	3240	742	1784	2526
VULCAIN 2	-	-	-	-	40.9	275.6	316.5
AESTUS 2	-	-	-	-	5.02	11.04	16.06

Table D-9: Feed system pump parameters

	mass flow [kg/s]			p_{out} [MPa]		η_p [%]	
Engine	fuel	ox	total	fuel	ox	fuel	ox
HM7B	2.57	11.7	14.27	5.55	5.02	60.0	73.0
LE-5	3.59	19.7	23.29	6.04	5.19	61.2	65.3
S-4(MA-3)	36.9	84.1	121.0	7.05	6.80	-	-
H-1	102.4	234.9	337.3	7.1	6.3	71	75
HM60	39.7	202.5	242.2	15.8	13.0	73.0	76.0
J2	38.2	212.1	250.3	8.62	7.64	73.0	80.0
RS-27	111.3	251.8	363.1	7.09	7.25	71.8	77.9
F-1	796	1804	2600	13.0	11.0	-	-
VULCAIN 2	44.9	274	-	-	-	-	-
AESTUS 2	-	-	-	-	-	-	-

Table D-10: Feed system turbine parameters

	p_{in}/p_{out} [−]		η_T [%]		P_T [kW]	
Engine	fuel	ox	fuel	ox	fuel	ox
HM7B	16.7	=	45.0	=	404	=
LE-5	4.59	1.85	47.6	39.2	472	132
S-4(MA-3)	-	=	-	=	1257	=
H-1	18.21	=	66.0	=	2830	=
HM60	17.0	13.6	59.0	27.0	11200	3000
J2	7.2	2.65	60.0	47.0	6404	1717
RS-27	22.0	=	58.9	=	3346	=
F-1	16.3	=	60.5	=	40000	=
VULCAIN 2	15.5	12	-	-	14290	5130
AESTUS 2	-	-	-	-	-	-

Table D-11: Gas generator parameters

Engine	$\dot{m}_{gg}$ [kg/s]	T_{gg} [K]	p_{gg} [MPa]	MR_{gg} [-]
HM7B	0.25	860.0	2.3	0.87
LE-5	0.436	837.0	2.63	0.85
S-4(MA-3)	4.00	843.8	5.15	0.297
H-1	7.86	922	4.22	0.342
HM60	8.4	871	8.5	0.9
J2	3.19	922	4.7	0.94
RS-27	9.13	916	4.7	0.33
F-1	75.7	1062	6.76	0.416
VULCAIN 2	9.7	875	10.1	0.90
AESTUS 2	-	-	-	-

D-3 Staged Combustion Cycle Engines

Table D-12: General performance parameters

Engine	F [kN]	I_{sp} [s]	p_c [MPa]	A_e/A_t [−]	MR [−]	propellant	operation point
LE-7	1080.0	445.6	12.7	52.0	5.5	LOX-LH2	sea level

Table D-13: Physical parameters

Engine	L [m]	d_e [m]	d [m]	m_{dry} [kg]
LE-7	3.2	1.737	2.57	1714.0

Table D-14: Combustion chamber parameters

Engine	L_c [m]	d_c [m]	L^* [m]	m_c [kg]	A_c/A_t
LE-7	0.37	0.40	0.78	145.5	2.75

Table D-15: Injector parameters

	injector Δp [kPa]		feed Δp [kPa]		mass flow [kg/s]		
Engine	fuel	ox	fuel	ox	fuel	ox	total
LE-7	1038	4598	14300	4700	35.2	211.1	246.3

Table D-16: Feed system pump parameters

	mass flow [kg/s]			p_{out} [MPa]		η_p [%]	
Engine	fuel	ox	total	fuel	ox	fuel	ox
LE-7	35.7	211.1	246.8	27.0	17.4	69.7	0.765

Table D-17: Feed system turbine parameters

	p_{in}/p_{out} [−]		η_T [%]		P_T [kW]	
Engine	fuel	ox	fuel	ox	fuel	ox
LE-7	1.49	1.38	68.9	47.9	18000	4500

D-4 Expander Cycle Engines

Table D-18: General performance parameters

Engine	F [kN]	I_{sp} [s]	p_c [MPa]	A_e/A_t [−]	MR [−]	propellant	operation point
Vinci	180	464	6.1	240	5.8	LOX-LH2	altitude
RL10A-3-A	73.4	446.4	3.2	61.1	5.0	LOX-LH2	altitude

Table D-19: Physical parameters

Engine	L [m]	d_e [m]	d [m]	m_{dry} [kg]
Vinci	4.20†	2.2	-	550
RL10A-3-A	1.78	1.0	1.0	138.0

†: with nozzle deployed, witch nozzle retracted engine length is only 2.37 m

Table D-20: Combustion chamber parameters

Engine	L_c [m]	d_c [m]	L^* [m]	m_c [kg]	A_c/A_t
Vinci	-	-	-	-	-
RL10A-3-A	0.335	0.262	0.95	-	2.95

Table D-21: Injector parameters

	injector Δp [kPa]		feed Δp [kPa]		mass flow [kg/s]		
Engine	fuel	ox	fuel	ox	fuel	ox	total
Vinci	-	-	-	-	-	-	-
RL10A-3-A	558	317	3951	1076	2.8	14.0	16.8

Table D-22: Feed system pump parameters

	mass flow [kg/s]			p_{out} [MPa]		η_p [%]	
Engine	fuel	ox	total	fuel	ox	fuel	ox
Vinci	5.81	33.69	-	22.4	8.1	-	-
RL10A-3-A	2.8	14.0	16.8	7.18	4.31	55.5	64.0

Table D-23: Feed system turbine parameters

	p_{in}/p_{out} [$-$]		η_T [%]		P_T [kW]	
Engine	fuel	ox	fuel	ox	fuel	ox
Vinci	-	-	-	-	-	-
RL10A-3-A	1.41	=	72	=	563	=

Appendix E

Pump and Turbine Efficiency

This appendix elaborates on the pump and turbine efficiency. Typical ranges are shown, efficiency dependencies are discussed and an average efficiency and the standard deviation for pump and turbine each are determined.

E-1 Pump efficiency

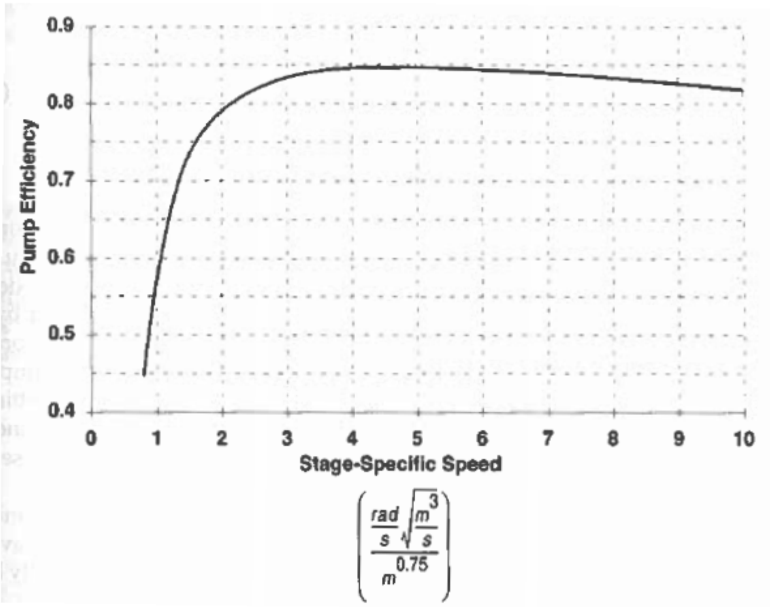


Figure E-1: Pump efficiency versus stage specific speed [14]

E-2 Pump Rotational Speed and Efficiency Dependency on Propellant Choice

In this section the hypothesis that dual shaft turbo-pump arrangements are commonly found for LOX-LH2 bi-propellant rockets because of the large difference in density of LOX and LH2 which is not the case for other propellant combinations.

- The pump head is defined as [14]:

$$H_p = \frac{\Delta p_p}{g_0 \cdot \rho} \tag{E-1}$$

where Δp_p is the required rise in pump pressure and ρ is the density of the propellant.

- The pump rotational speed follows from [14]:

$$N_r = \frac{u_{ss} \cdot NPSH^{0.75}}{\sqrt{Q}} \tag{E-2}$$

$$\tag{E-3}$$

where u_{ss} is the suction specific speed and can be taken equal to 130 for liquid hydrogen, 90 for other cryogenic liquids and 70 for all other propellants. [14] And NPSH is the Net Positive Suction Head which is found by using following relation [14]:

$$NPSH = \frac{p_i - p_v}{g_o \cdot \rho} \tag{E-4}$$

with p_i the pump inlet pressure and p_v the propellant vapour pressure.
The number of pump stages n is equal to the next higher integer of the following ratio [14]:

$$n \geq \frac{\Delta p_p}{\Delta p_{ps}} \tag{E-5}$$

where for the allowable pressure rise over a single stage (Δp_{ps}) 16 MPa for liquid hydrogen and 47 MPa for all other propellants can be used. [14]

- The pump efficiency is dependant on the stage specific speed as can be seen from figure E-1. The stage specific speed is determined by the pump rotational speed N_r, the pump capacity or volumetric flow Q and the pump head H_p [14]:

$$N_s = \frac{N_r \cdot \sqrt{Q}}{\frac{H_p}{n}} \tag{E-6}$$

Hence as can be seen from eq.E-1 and eq.E-4, both the pump head and net positive suction head are inverse proportional to the density of the propellant; the larger the density the smaller the pump head and net positive suction head. Combination of eq.E-1. eq.E-4 , eq.E-2 and eq.E-6 then yield:

$$
\begin{aligned}
N_s &= \frac{N_r \cdot \sqrt{Q}}{\frac{H_p}{n}} \\
&= \frac{\left[\frac{u_{ss} \cdot NPSH^{0.75}}{\sqrt{Q}}\right] \cdot \sqrt{Q}}{\frac{H_p}{n}} \\
&= \frac{\left[\frac{u_{ss} \cdot \left(\frac{p_i - p_v}{g_o \cdot \rho}\right)^{0.75}}{\sqrt{Q}}\right] \cdot \sqrt{Q}}{\frac{\left(\frac{\Delta p_p}{g_0 \cdot \rho}\right)}{n}} \\
&= \frac{u_{ss} \cdot \left(\frac{p_i - p_v}{g_o \cdot \rho}\right)^{0.75} \cdot g_0 \cdot \rho \cdot n}{\Delta p_p} \\
&= \frac{u_{ss} \cdot \left(\frac{p_i - p_v}{g_o}\right)^{0.75} \cdot g_0 \cdot \rho^{0.25} \cdot n}{\Delta p_p}
\end{aligned}
$$

Hence with increasing density the stage specific speed is increasing which to a certain point increases pump efficiency.

In other words when having a direct drive arrangement, the pump stage specific speed of both pumps is the same and must be taken equal to the one with the lowest stage specific speed and hence lowest efficiency. Relation eq.E-2 shows the dependency of the pump rotational speed to the density; the lower the density the lower the pump speed. A geared arrangement driving a LOX and LH2 pump is therefore larger and heavier due to the high reduction ratio, and thus larger gears needed.

E-3 Turbine Efficiency

Figure E-2 was taken from [14] and shows the turbine efficiency of 50% reaction turbines and impulse turbines with on, two and three rotors against the non dimensional ratio of mean pitchline velocity over spouting velocity. Humble et al. mentions in [14] that turbine losses such as viscous, friction or leakage losses can reduce the shown values to 95% of the shown values and even 75% for small turbines. As the largest efficiency in figure E-2 is about 90%, this hence means that in practice an efficiency of $0.95 \cdot 0.9 = 0.855$ or 85.5% is achievable. Similarly for small turbines this number becomes $0.75 \cdot 0.9 = 0.675$ or 67.5%.

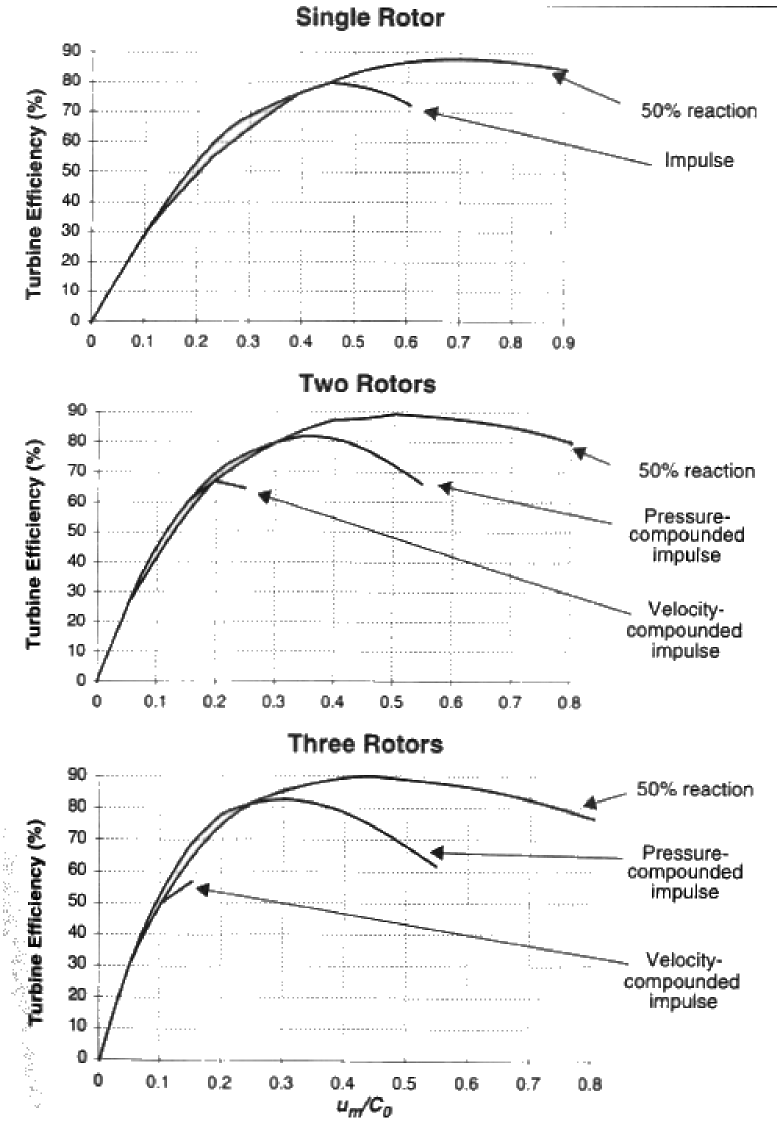


Figure E-2: Turbine efficiency versus ratio of pitchline velocity (u_m) over spouting velocity (C_0) [14]

E-4 Pump and Turbine Average Efficiency and Standard Deviation Using Real Engine Data

Table E-1: Calculation of estimate of pump and turbine efficiency standard deviation. Data source: [9]

Engine		Pump efficiency	Turbine efficiency
HM7B	fuel side	0.600	0.450
	ox side	0.730	-
RL10-3-3A	fuel side	0.570	0.720
	ox side	0.640	-
LE-5	fuel side	0.612	0.476
	ox side	0.653	0.392
LR91	fuel side	0.600	0.530
	ox side	0.665	-
5C	fuel side	0.650	0.500
	ox side	0.660	-
H-1	fuel side	0.710	0.660
	ox side	0.750	-
HM60	fuel side	0.730	0.590
	ox side	0.760	0.270
J-2	fuel side	0.730	0.600
	ox side	0.800	0.470
RS-27	fuel side	0.718	0.589
	ox side	0.779	-
LE-7	fuel side	0.697	0.689
	ox side	0.765	0.479
LR87	fuel side	0.630	0.520
	ox side	0.670	-
SSME	fuel side	0.760	0.605
	ox side	0.681	-
AVG		0.690	0.534
STD		0.064	0.115

Appendix F

Construction of Pressure-fed Engine Overall Engine Length and Diameter Relationships

For pressure fed engines relations F-1 and F-2 were established based on pressure-fed rocket engines found in literature. App.F explains how the relations were obtained.

$$L = 1.4921 \cdot \ln(F_{vac}) - 13.179 \tag{F-1}$$

$$d = 0.8364 \cdot \ln(F_{vac}) - 7.1771 \tag{F-2}$$

The length and diameter of the engines are the length and diameter of the smallest cylindrical-shaped enclosure that contains the turbo-pump completely. [15].

In order to obtain a engine diameter and length estimation relation for a pressure fed engine, a regression analysis is performed on available data found in literature. Table F-1 shows five upper stage pressure fed engines of which dimension data was found in Jane's space directory [12] and Encyclopedia Astronautica [16]. Taking the thrust as variable and a log curve fit to the data relation F-1 and F-2 were obtained; this is also visualised in Figure F-1 and F-2. For the AJ10-188K and Transtar no diameter was found in literature, however a photo of each engine (see Figure F-3 and Figure F-4) was used to derive the diameter knowing the length and using the aspect ratio of the picture:

$$D_{real} = \frac{L_{real}}{L_{picture}} \cdot D_{picture} \tag{F-3}$$

The same approach could be used to estimate the engine length of the liberty-2 engine, for which only the overall engine diameter was found, however no photograph was found and hence this engines length remains unknown. The relative standard deviation of each relation is calculated as well in Table F-1.

Table F-1: Pressure-fed engine length and diameter relationship and RSD determination, sources: [12],[16]

Engine	F_{vac} [N]	L [m]	est. L† [m]	D [m]	est. D‡ [m]
Aestus	27500	2.195	2.0732	1.263	1.3725
AJ10-118K	43380	2.69	2.7533	1.7	1.7538
Transtar	16680	1.27	1.3271	*0.6529*	0.9544
AJ10-137	97500	3.9624	3.9617	*2.4765*	2.4311
Liberty-2	17800	?	-	1.43	1.0087
AVG [kg]			2.5288		1.5041
SD [kg]			0.09		0.19
RSD [%]			3.40		12.60

italic values are estimated values using fig.F-1 and fig. F-2 and relation F-3.
†: estimated value using relation F-1
‡: estimated value using relation F-2

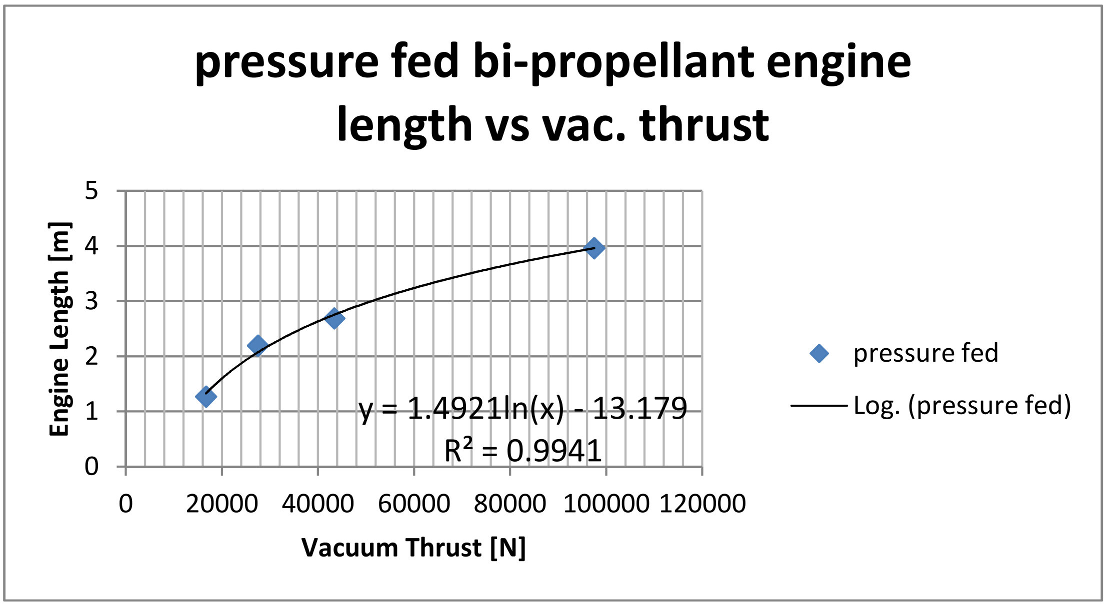


Figure F-1: Plot of length versus vacuum thrust data of Table F-1

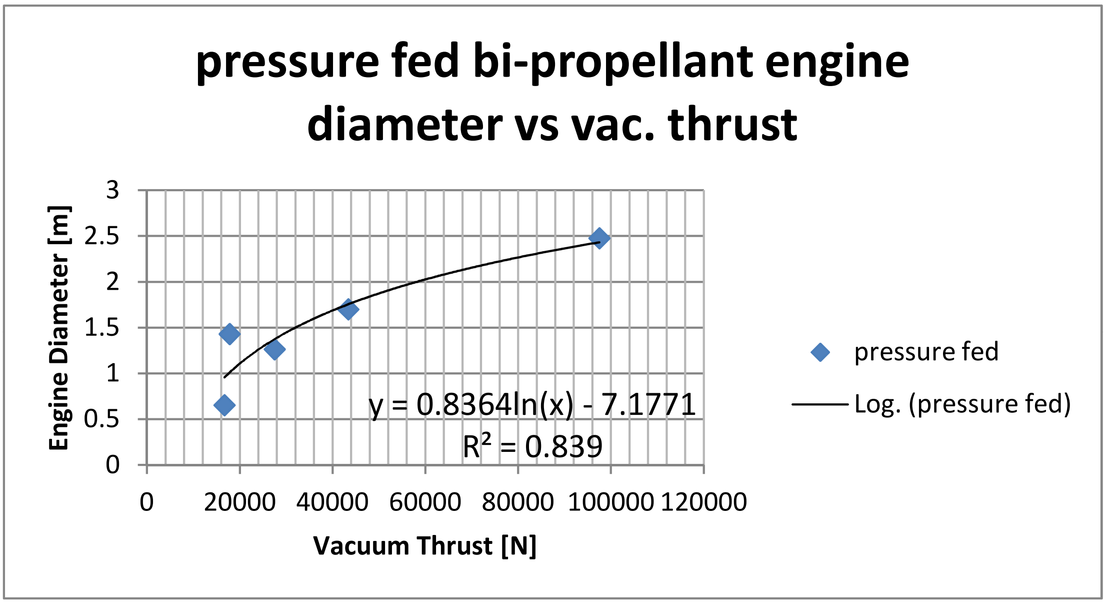


Figure F-2: Plot of diameter versus vacuum thrust data of Table F-1

Figure F-3: Picture of the AJ10-137 engine, source: [17]

Figure F-4: Advertisement poster for the Transtar engine, source [18]

Appendix G

Determination of Stage Dry Mass Correction Factor

In this appendix the dry mass correction factor that is needed to correct the propulsion system mass estimate by LiRA to a stage dry mass is determined. In [19] total mass, propellant mass and burn time data for several launcher stages are available. In Table G-1 selection of those stages of which the engines can be modelled with LiRA and of which the engine data is also available, is made; these engines are ran with the LiRA engine analysis routine and yield a propulsion system dry mass estimate. Dividing the real stage dry mass with this estimate yields a correction factor. The average of the correction factor of all selected stages is determined along with its standard deviated and used as final correction factor in LiRA.

Table G-1: Determination of stage dry mass correction factor

Launcher	Stage	Engine	t_b [s]	m_{tot} [kg]	Real m_{prop} [kg]	m_{dry} [kg]	Calculated m_{dry} [kg]	K [−]
Ariane 5	EPS-V	AESTUS	1000	11300	10000	1300	641.5735	2.03
Delta 2	second stage	AJ10-118K	431.6	6950	6000	950	365.8649	2.60
Ariane 4	third stage	HM7B	780	13500	11800	1700	695.7583	2.44
Ariane 5	ESC-A	HM7B	945	19400	14900	4540	813.9162	5.58
Delta IV	4 m Second Stage	RL10B-2	840	23200	20400	2780	1141	2.44
Zenit 2	second stage	RD-120	249	89500	80600	8900	8550.4	1.04
Titan 4	Centaur T	RL10A-3-3A	600	23900	21000	2930	651.3612	4.50
Delta IV	CBC First stage	RS-68	242	231000	204000	27000	15813.0	1.71
Ariane 5	EPC generic	Vulcain	600	170000	158000	12000	8690.2	1.38
Ariane 5	EPC Evolution	Vulcain 2	540	189000	175000	14000	9031.3	1.55
AVG								2.53
STD								1.44

Appendix H

Calculation of Thrust Chamber Mass Correction Factor K

In this appendix the thrust chamber mass correction factor is calculated using the method proposed by Zandbergen in [3]. Table H-2 shows the engine data needed and the estimates that need to be made using eq.H-1 , eq.H-2 and eq.H-3 [3]:

$$V_c = \frac{\pi}{4} \cdot d_c^2 \cdot L_c \tag{H-1}$$

$$M_{\text{shell,cylindrical chamber}} = \left(\frac{d_c}{L} + 2\right) \cdot \frac{\rho}{\sigma} \cdot f_s \cdot \cdot p_c \cdot V_c \tag{H-2}$$

$$M_{\text{shell,conical nozzle}} = \frac{\rho}{\sigma} \cdot f_s \cdot \left(A_i \cdot \frac{\epsilon - 1}{\sin(\alpha)} \cdot \frac{p_c \cdot d_c}{2}\right) \tag{H-3}$$

where at least a safety factor (f_s) of 2 should be taken. [3]

The divergence half angle follows from the nozzle throat radius, nozzle exit radius and nozzle length [14]:

$$L = \frac{r_e - r_t}{\tan(\alpha)} \tag{H-4}$$

The calculations were performed for five engines for which data was collected, however for only three of them also the thrust chamber mass was available and thus the correction coefficient could be calculated. It is assumed that the wall temperatures are at chamber temperature by the use of ablative layer (for example in the viking engine) or film cooling. Therefore the mentioned ultimate strengths of the materials are those at room temperature.

Using the results for the correction factor of the Viking, Vulcain and Vulcain 2, an average value of 1.52 with a standard deviation of 0.80 is found.

Table H-1: Typical thrust chamber inner wall materials and their properties at room temperature

Material	ρ^* [kg/m^3]	$\sigma^\dagger_{ult}$ [MPa]	$k^\ddagger$ [W/mK]
A-286	7940	620	15.1
Columbium$^\circ$	8300	310	52
Inconel 600	8470	1040	585
Haynes 188	8980	945	17.5
Narloy Z	9300	192	310

* density, sources: [20], [14], [21], [22], [23]
† ultimate strength, sources: [20], [14], [21], [22], [23]
‡ thermal conductivity, sources: [20], [24], [21], [22], [23]
$^\circ$ also known as Niobium

Table H-2: Example calculation of thrust chamber correction factor for several engines. Source engine data: [3], [23], [25]

	Viking	ATE	Vulcain	LE-5	Vulcain 2	
Combustion chamber						
Material	[–]	Haynes 188	Narloy Z	Narloy Z	A286	Narloy Z
Diameter	[m]	0.53	0.119	0.415	0.24	0.360
Length	[m]	1.3	0.179	0.426	0.351	0.418
Calculated volume*	[m^3]	0.287	0.002	0.058	0.016	0.042
Pressure	[bar]	58	90	110	36.8	117
Calculated shell mass	[kg]	76.1	4.6	182.6	4.0	138.1
Nozzle						
Material	[–]	Haynes 188	Haynes 188	Inconel 600	A-286	Inconel 600
Inlet diameter	[m]	0.49	0.254	0.59	0.418	0.270
Exit diameter	[m]	0.99	0.72	1.76	1.608	2.09
Length	[m]	1.207	0.85	1.8	1.843	2.543
Extension area ratio	[–]	10.5	11.2	9.31	14.8	60
Calculated divergence angle$^\circ$	[rad]	0.2042	0.2675	0.3142	0.3123	0.3437
Calculated shell mass †	[kg]	258.0	19.9	274.6	69.7	345.7
Thrust chamber mass						
Calculated ‡	[kg]	334.1	22.7	383.9	73.7	428.4
Actual	[kg]	443	-	625	-	909
Correction factor	[–]	1.33	?	1.37	?	1.88

* calculated using eq.H-1
$^\circ$ calculated using eq.H-4
† calculated using eq.H-2
‡ calculated using eq.H-3

Appendix I

Validation Tables

In this appendix the quantitative validation of LiRA's estimates of certain output parameters takes place. The accuracy of the estimates and whether or not this is an acceptable value, is given by the Standard Error of Estimate (SEE) and Relative Standard Error of Estimate (RSE) respectively.

The SEE is to be interpreted just the same as a regular standard deviation (SD); the latter is an indication of how spread out a distribution of estimates is with respect to the mean of the distribution of estimates while the former (SEE) indicates the spread of predictions/estimates with respect to their expected/real values.

Estimates with high RSE values are considered less reliable than estimates with low RSE values; but where to put the boundary is subjective. In this work a value of 30% is taken as upper limit for the relative standard error of estimate to still consider the estimate reliable.

I-1 Performance Model

The performance model is validated by comparing results with actual data. Parameters checked are the pump discharge pressures, the mass flows passing the pumps and, if applicable go through the gas generator or pre-burner. For the gas generator cycle LiRA's estimate of gas generator pressure and mixture ratio is also interesting and thus compared. Further the turbine power, the vacuum thrust and vacuum specific impulse estimate of the model are compared as well. The rationale for taking these parameters for comparison are that they are available for several engines. In the ideal case every parameter should be validated but as the available data is limited because a lot of data is confidential only the parameters that have been found for more than one engine are validated. As parameters such as mass flow and power are dependant on many other parameters, a close match between calculated values and real values suggest that that the parameters that they are construct from are also likely to match closely to reality. However when parameters show significant differences it is harder to trace which parameter(s) are causing the error. The validation of specific impulse and thrust is found in table I-1.

Table I-1: Vacuum Isp and vacuum thrust comparison with their respective actual values using data from [9], [2], [13], [26], [27], [28], [29], [30], [16] and [31]

Engine	Real		Calculated		$E_{\%}$ [%]	
	$(I_{sp})_{vac}$ [s]	F_{vac} [kN]	$(I_{sp})_{vac}$ [s]	F_{vac} [kN]	$(I_{sp})_{vac}$	F_{vac}
Aestus	324	30	332.3	33.1	2.6	10.3
Aestus 2	340	55.4	353.8	52.4	4.1	5.4
F-1	304.8	7775.5	307.6	8615.5	0.9	10.8
H-1	292	945.4	288.5	980.5	1.2	3.7
HM7B	446	62.2	456.3	62	2.3	0.3
J2	424	1023	418.1	1132	1.4	10.7
J2S	436	1178.8	429.3	1197.7	1.5	1.6
LE-5	450	103	460	106.6	2.2	3.5
LE-7	445.6	1078.7	431.4	1087.3	3.2	0.8
RD-120	350	833.6	349.8	808.6	0.1	3.0
RD-170	337	1976	329.3	1885.5	2.3	4.6
RL10A-3-3A	446.4	73.4	444.8	79.5	0.4	8.3
RL10B-2	462	110	470.6	120.2	1.9	9.3
RS-27	294	1043	299.7	1080.7	1.9	3.6
S-4(MA-3)	308.7	364	317.4	370.8	2.8	1.9
SSME	452.9	2091	442.2	2041	2.4	2.4
Vinci	465	180	469	189	0.9	5.0
Vulcain	440	1025	436.3	967.9	0.8	5.6
Vulcain 2	429	1350	424.5	1263.7	1.0	6.4
SEE			8.1	203.2		
RSE [%]			2.1	17.5		

Table I-2: Pump discharge pressures

Engine	Cycle	Calculated value [bar]		Real value [bar]		$E_{\%}$ [%]	
		$p_{p,ox}$	$p_{p,fuel}$	$p_{p,ox}$	$p_{p,fuel}$	$p_{p,ox}$	$p_{p,fuel}$
F-1	gg	111.0	171.3	110	130	0.9	31.8
H-1	gg	57.4	59.0	63	71	8.9	16.9
HM7B	gg	48.2	49.3	50.2	55	4.0	10.4
J2	gg	75.0	75.8	76.4	86.2	1.8	12.1
LE-5	gg	49.2	50.3	51.9	60.4	5.2	16.7
LE-7	sc	180.1	271.0	174	270	3.5	0.4
RL10A-3-3A	ce	43.9	45.4	43.1	71.8	1.9	36.8
RS-27	gg	67.8	82.6	72.5	70.9	6.5	16.5
S-4(MA-3)	gg	62.9	64.7	68	70.5	7.5	8.2
Vulcain	gg	137.2	138.5	130	158	5.5	12.3
SEE		4.5	19.3				
RSE [%]		5.4	19.1				

Table I-3: Oxidiser and fuel mass flow rates of pressure fed engines

Engine	Cycle	Calculated value [kg/s]		Real value [kg/s]		$E_{\%}$ [%]	
		m_{ox}	m_{fuel}	m_{ox}	m_{fuel}	m_{ox}	m_{fuel}
Aestus	pf	6.7	3.5	5.89	2.87	12.9	22.0
SEE		?	?				
RSE [%]		?	?				

Table I-4: Oxidiser pump (main combustion chamber ($_c$) and gas generator ($_{gg}$) mass flow. Sources: [6], [32], [9], [3], [12]

Engine	Cycle	Calculated value [kg/s]			Real value [kg/s]			$E_\%$ [%]		
		$(\dot{m}_p)_{ox}$	$(\dot{m}_p)_{fuel}$	$\dot{m}_{gg}$	$(\dot{m}_p)_{ox}$	$(\dot{m}_p)_{fuel}$	$\dot{m}_{gg}$	$(\dot{m}_p)_{ox}$	$(\dot{m}_p)_{fuel}$	$\dot{m}_{gg}$
F-1	gg	1989.3	913.6	47.1	1804	796	75.7	10.3	14.8	37.8
H-1	gg	240.5	109.0	3.0	234.9	102.4	7.86	2.4	6.4	61.8
HM7B	gg	11.5	2.6	0.2	11.7	2.57	0.25	1.7	1.2	20.0
J2	gg	236.5	45.6	6.1	212.1	38.2	3.19	11.5	19.4	91.2
LE-5	gg	20.3	4.0	0.7	19.7	3.59	23.29	3.0	11.4	97.0
RS-27	gg	254.8	116.2	3.3	251.8	111.3	9.13	1.2	4.4	63.9
S-4(MA-3)	gg	82.8	37.1	0.7	84.1	36.9	4	1.5	0.5	82.5
Vulcain	gg	192.9	41.4	8.1	202.5	39.7	9.1	4.7	4.3	11.0
Vulcain 2	gg	267.4	43.1	7.0	274	44.9	6	2.4	4.0	16.7
SEE		66.2	41.8	13.3						
RSE [%]		18.1	28.6	156.6						
LE-7	sc	220.3	36.7	74.1	211.1	35.7	53	4.4	2.8	39.8
RD-0120	sc	428.0	71.3	129.1	376.8	62.8	78.6	13.6	13.5	64.2
RD-120	sc	170.2	65.5	173.6	175.4	64.5	?	4.0	1.6	?
RD-170	sc	423.1	160.9	434.4	432.0	166.2	?	3.9	3.2	?
SEE		30.6	5.8	54.7						
RSE [%]		9.9	7.0	27.0						
LE-5A	be	22.1	4.6	N/A	19.7	3.59	N/A	12.2	28.1	N/A
RL10A-3-3A	ce	15.2	3.0	N/A	14	2.79	N/A	8.6	7.5	N/A
RL10B-2	ce	22.3	3.8	N/A	19.9	3.3	N/A	12.1	15.2	N/A
Vinci	ce	35.0	6.0	N/A	33.7	5.8	N/A	3.9	3.4	N/A
SEE		2.2	0.7	N/A						
RSE [%]		9.3	15.4	N/A						

Table I-5: Turbine oxidiser side ($(_t)_{ox}$) and turbine fuel side ($(_t)_{fuel}$) power. Sources: [6], [32], [9]

Engine	Cycle	Calculated value [kW]		Real value [kW]		$E_\%$ [%]	
		$(P_t)_{ox}$	$(P_t)_{fuel}$	$(P_t)_{ox}$	$(P_t)_{fuel}$	$(P_t)_{ox}$	$(P_t)_{fuel}$
F-1	gg	=	50140	=	40000	=	25.4
H-1	gg	=	2728.3	=	2830	=	3.6
HM7B	gg	=	369.6	=	404	=	8.5
RS-27	gg	=	3641.6	=	3346	=	8.8
S-4(MA-3)	gg	=	942.3	=	1257	=	25.0
Vulcain	gg	3129.0	12264	3000	11200	4.3	9.5
Vulcain 2	gg	4836.4	14366	5100	14500	5.2	0.9
SEE		293.5	4166.7				
RSE [%]		7.4	34.5				

Table I-6: Validation of eq.I-1. Data sources: [9] and [13]

Engine	Real			Calculated			$E_{\%}$ [%]		
	L_c [m]	d_c [m]	A_c/A_t [-]	L_c [m]	d_c [m]	A_c/A_t [-]	L_c	d_c	A_c/A_t
HM7B	0.283	0.18	2.78	0.3229	0.1936	3.16	14.1	7.6	12.0
RL10A-3-3A	0.335	0.262	2.95	0.3443	0.2246	2.98	2.8	14.3	1.0
LE-5	0.351	0.24	3.11	0.3522	0.2373	2.9	0.3	1.1	7.2
S-4(MA-3)	2.18	0.303	1.66	0.5234	0.3801	2.43	76.0	25.4	31.7
H-1	2.18	0.53	1.67	0.6112	0.632	2.08	72.0	19.2	19.7
HM60*	0.426	0.415	2.99	0.4345	0.4198	2.38	2.0	1.2	25.6
J-2	0.4572	0.47	1.58	0.4773	0.5714	2.14	4.4	21.6	26.2
RS-27	2.34	0.52	1.62	0.6034	0.6031	2.1	74.2	16.0	22.9
LE-7	0.37	0.4	2.75	0.4188	0.3759	2.44	13.2	6.0	12.7
F-1	3.35	1.02	-	0.7125	1.2216	-	78.7	19.8	-
SSME	0.356	0.45	2.96	0.4283	0.402	2.35	20.3	10.7	26.0
LR87	0.51	0.55	2.08	-	-	2.14	-	-	2.8
LR91	0.391	0.367	2.51	-	-	2.46	-	-	2.0
5C	0.5	1.3	-	-	2.27	-	-	42.7	-
SEE				1.232	0.089	0.51			
RSE [%]				259.3	18.5	21.0			

* also known as Vulcain

I-2 Dimensioning and Mass Model

The dimension and mass estimation relations are based on first estimate equations which use performance or correction factors, or on empirical equations obtained by regression analysis of actual engine data. The accuracy of the used relations is expressed by the standard deviation, also known as the Standard Error of Estimate (SEE); in order to determine the SEE of each relation an attempt to find actual engine data and test the equation against it was made; however since this type of rocket engine data is often not openly available this was not possible for all components. Some components such as ignitor, starter, electrical system, hydraulic control system and flight instrumentation system are not considered at all as these are only minor components and negligible for the purposes of this work. Table I-6 till Table I-14 give the results for several performance, dimension and mass relations.

I-2-1 Thrust Chamber

The validation of combustion chamber dimensions and the contraction ratio relation

$$\frac{A_{mcc}}{A_t} = 8.0 \cdot d_t^{-0.6} + 1.25 \text{ where } d_t \text{ is in cm} \tag{I-1}$$

is performed in table I-6.

The mass of the combustion chamber is not calculated separately in LiRA, instead a mass for the thrust chamber (hence combination of combustion chamber and nozzle) is estimated using eq.I-2:

$$m_{\text{thrust chamber}} = K \cdot (m_{\text{thrust chamber}})_{shell} = K \cdot [(m_c)_{shell} + (m_{nozzle})_{shell}] \tag{I-2}$$

the SEE of this equation using a thrust chamber mass correction factor of 1.52 is calculated in table I-7

Table I-7: Thrust chamber mass validation

Engine	Real mass [kg]	Estimated mass [kg]	$E_{\%}$ [%]
Viking	443	509.2	14.9
Vulcain	625	696.7	11.5
Vuclain 2	909	737.3	18.9
SEE		139.6	
RSE [%]		21.6	

I-2-2 Turbo-pump

Turbo-pump mass estimation relation RSE value already constructed by Zandbergen in [33].

I-2-3 Gas Generator or Pre-burner

The estimation of gas generator pressure and mixture ratio in the gas generator cycle and staged combustion cycle is performed in Table I-8.

Table I-8: Gas generator pressure and mixture ratio in gas generator cycles

Engine	Calculated value		Real value		$E_{\%}$ [%]	
	p_{gg} [bar]	MR_{gg} [−]	p_{gg} [bar]	MR_{gg} [−]	p_{gg}	MR_{gg}
F-1	117.7	0.17	67.6	0.416	74.1	59.1
H-1	48.5	0.1	42.2	0.342	14.9	70.8
HM7B	40.6	0.87	23	0.87	76.5	0.0
J2	62.8	0.94	47	0.94	33.6	0.0
LE-5	41.4	0.85	26.3	0.85	57.4	0.0
RS-27	62.7	0.15	47	0.33	33.4	54.5
S-4(MA-3)	53.1	0.15	51.5	0.297	3.1	49.5
Vulcain	114.3	0.89	85	0.9	34.5	1.1
Vulcain 2	134.1	0.90	101	0.9	32.8	0.0
SEE	26.3	0.147				
RSE [%]	35.1	26.4				

I-2-4 Propellant Tanks

The propellant tank mass estimation relation

$$m_{tank} = \frac{V_t \cdot MEOP}{K} \tag{I-3}$$

is validated by letting it estimate real tank masses. The SEE of eq.I-3 for surface tension tanks using a tank performance factor of 3.32×10^4 is calculated in table I-10.

Table I-9: Propellant tank volume validation

Launcher	Stage	Engine	Real		Calculated		$E_{\%}$ [%]	
			$V_{tank,ox}$ [m^3]	$V_{tank,fuel}$ [m^3]	$V_{tank,ox}$ [m^3]	$V_{tank,fuel}$ [m^3]	$V_{tank,ox}$	$V_{tank,fuel}$
Ariane 5	EPC	Vulcain	120	390	105	390	12.5	0.0
	EPS	Aestus	2.936	2.936	5.193	4.621	76.9	57.4
	ESC-A	HM7B	11.36	39.41	10.31	38.83	9.2	1.5
SEE					10.8	1.3		
RSE [%]					26.8	0.9		

Table I-10: Surface tension tanks [34]

Tank name	Tank volume [m^3]	MEOP [Pa]	Mass [kg]	Est. mass [kg]	$E_{\%}$ [%]
OST 31/0	0.104	2460000	6.4	7.7	20.4
OST 31/1	0.177	2400000	6.4	12.8	99.9
E3000 LLX	0.745	2250000	39.5	50.5	27.8
E3000 LX	0.651	2250000	35.9	44.1	22.9
SEE				8.8	
RSE [%]				30.5	

I-2-5 Pressurant Tanks

The pressurant tank volume is validated estimating tank volumes of actual launcher stages. However only those stages where both oxidiser as fuel are pressurised by the same pressurant can be used for comparison.

Table I-11: Pressurant tank volume validation

Launcher	Stage	Engine	Real $V_{tank,press}$ [m^3]	Calculated $V_{tank,press}$ [m^3]	$E_{\%}$ $V_{tank,press}$ [%]
Ariane 5	EPS	Aestus	0.6	0.8	33.3
SEE				?	
RSE [%]				?	

The pressurant tank mass estimation relation is validated by letting it estimate real tank masses; as for pressurant tanks both Composite Over-wrapped Pressure Vessels or titanium tanks are often used, both type of tanks are validated seperateley.

Composite Over-wrapped Pressure Vessels (COPV)

The SEE of eq.I-3 for Composite Over-wrapped Pressure Vessels (COPV) using a tank performance factor of 1.22×10^5 is calculated in table I-12.

Table I-12: Composite Over-wrapped Pressure Vessels [35]

Tank name	Tank volume [m^3]	MEOP [Pa]	Mass [kg]	Est. mass [kg]	$E_{\%}$ [%]
80386-101	0.032	17236893	6	4.5	39.9
80412-1	0.050	15002992	7	6.2	13.6
80548-1	0.051	30998829	12	13.1	4.5
80458-201	0.054	19822427	12	8.8	39.4
80400-1	0.067	31026408	10	17.1	41.7
80402-1	0.067	31026408	10	17.1	41.7
80446-1	0.067	31026408	11	17.1	37.7
80459-1	0.067	31026408	11	17.1	37.7
80436-1	0.081	33094835	13	22.1	42.5
80465-1	0.081	33094835	13	22.1	42.5
80475-1	0.087	30998829	17	22.1	23.9
80458-101	0.120	19822427	13	19.4	34.7
80458-1	0.133	19822427	20	21.6	5.4
SEE				6.1	
RSE [%]				38.3	

Titanium tanks

The SEE of eq.I-3 for Monolithic Titanium Pressurant Tanks using a tank performance factor of 6.43×10^5 is calculated in table I-13.

Table I-13: Monolithic Titanium Pressurant Tanks [35]

Tank name	Tank volume [m^3]	MEOP [Pa]	Mass [kg]	Est. mass [kg]	$E_{\%}$ [%]
80326-1	0.004	24821126	2	1.5	3.1
80345-1	0.007	31026408	3	3.2	6.1
80119-105	0.007	4136854	1	0.5	74.2
80195-1	0.009	18374528	5	2.7	103.2
80202-1	0.015	31026408	7	7.0	2.3
80194-1	0.016	24821126	5	6.0	11.0
80198-1	0.019	25000390	8	7.3	4.9
80186-1	0.029	24959021	11	11.1	5.1
80295-1	0.002	55158058	1	1.4	3.3
80314-201	0.036	24821126	16	13.9	15.1
80383-1	0.036	24821126	16	13.9	15.1
80314-1	0.036	24821126	16	13.9	14.1
80221-1	0.088	20684272	25	28.4	12.4
80333-1	0.106	27992715	36	46.0	21.2
80218-1	0.121	23442175	36	44.0	18.6
SEE				3.7	
RSE [%]				27.9	

I-2-6 Overall Engine

The overall engine mass is estimated using following relations:

- pressure fed

$$m_{engine} = \begin{cases} 0.1005 \cdot F^{0.6325} & \text{storable} \\ \text{no relation given} & \text{other} \end{cases} \tag{I-4}$$

with F, the thrust in Newton

- turbo-pump fed

$$m_{engine} = \begin{cases} 0.006 \cdot F^{0.858} \cdot p_{mcc}^{0.117} \cdot (A_e/A_t)^{0.034} & \text{cryogenic} \\ (0.001 \cdot F + 49.441) \cdot N^{0.030} \cdot (A_e/A_t)^{0.004} & \text{storable, semi-cryogenic} \end{cases} \tag{I-5}$$

with F, the thrust in Newton, p_{mcc} the chamber pressure in bar, (A_e/A_t) the nozzle area expansion ratio and N the amount of thrust chambers.

The dimensions of a turbo-pump fed engine are estimated using following relations:

$$L = 0.088 \cdot F^{0.255} \cdot N^{-0.40} \cdot (A_e/A_t)^{0.055} \tag{I-6}$$

$$d = 0.026 \cdot F^{0.265} \cdot N^{0.150} \cdot (A_e/A_t)^{0.184} \tag{I-7}$$

where F denotes the thrust, N the number of thrusters and A_e/A_t the expansion ratio respectively.

Table I-14: Engine dry mass, overall length and overall diameter validation

Engine	Cycle	Real			Calculated			$E_{\%}$ [%]		
		M_{dry} [kg]	L [m]	d [m]	$M^{\star}_{dry}$ [kg]	L† [m]	d‡ [m]	M_{dry}	L	d
Pressure fed - storable and semi-storable										
Aestus	pf	111	2.195	1.263	72.6	2.349	1.527	34.6	7.0	20.9
AJ10-118K	pf	124.7	2.69	1.7	102.9	3.173	1.989	17.5	18.0	17.0
SEE					44.2	0.507	0.392			
RSE [%]					50.3	18.4	22.3			
Turbo-pump fed - cryogenic										
HM60*	gg	1719	3.1	2.5	1785.3	3.752	2.082	3.9	21.0	16.7
HM7B	gg	158	2.01	0.992	137.2	1.871	1.091	13.2	6.9	10.0
J2	gg	1542	3.38	2.05	1674.8	3.693	1.923	8.6	9.3	6.2
LE-5	gg	255	2.7	1.65	222.8	2.211	1.388	12.6	18.1	15.9
LE-5A	be	244	2.668	1.625	249.6	2.273	1.414	2.3	14.8	13.0
LE-7	sc	1714	3.2	2.57	1835.2	3.786	2.140	7.1	18.3	16.7
RL10-3-3A	ce	138	1.78	1	166.1	1.960	1.102	20.4	10.1	10.2
RL10-B-2	ce	259	4.153	2.223	258.6	2.371	1.633	0.1	42.9	26.6
SSME	sc	3150	4.24	2.39	3366.1	4.544	2.721	6.9	7.2	13.8
Vulcain 2	gg	1850	3.6	2.15	2067.7	3.958	2.273	11.8	9.9	5.7
SEE					121.6	0.723	0.331			
RSE [%]					10.3	23.8	18.6			
Turbo-pump fed - storable and semi-storable										
H-1	gg	878.2	2.67	1.24	1038.5	3.326	1.475	18.3	24.6	19.0
RD-120	sc	1125	3.872	1.954	874.2	3.652	2.258	22.3	5.7	15.6
RS-27	gg	1146.6	3.77	1.69	1141.5	3.487	1.631	0.4	7.5	3.5
RS-72**	gg	138	2.286	1.3	104.2	1.924	1.323	24.5	15.8	1.7
S-4(MA-3)	gg	470.4	2.41	1.22	425.7	2.764	1.406	9.5	14.7	15.3
SEE					151.5	0.452	0.216			
RSE [%]					21.1	14.9	13.3			

⋆ Dry mass: calculated using eq.I-4 if pressure fed or I-5 if turbo-pump fed
† Engine length: calculated using eq.F-1 if pressure fed or I-6 if turbo-pump fed
‡ Engine diameter: calculated using eq.F-2 if pressure fed or I-7 if turbo-pump fed
* also known as Vulcain
** also known as Aestus II

Appendix J

One-at-the-time First Order Sensitivity Analysis Calculation Example

For reasons of repeatability and understanding of the One-At-the-Time approach used in the sensitivity analysis of the selected decision and knowledge parameters, the intermediate calculation values are given in this appendix. LiRA also writes these tables to text files, hence the user has always the possibility to check calculations and/or to study how a certain value was obtained.

For the most important output parameters, total wet mass and total propulsion system volume, a probabilistic error analysis is performed by defining probability distributions of the values for the various input parameters.

Each investigated input variable is assigned a high and low value based on either the difference in known maximum and minimum for this value or from a known parameter's distribution. The model is executed varying each parameter one at the time to evaluate the impact of those variations on the model output. To limit the amount of executions only worst and best cases are considered, meaning the model is run for each input parameter one time with its lowest and one time with its highest value. The assumptions made here that all input parameters are independent from each other.

The first order one-at-the-time sensitivity analysis follows the method suggested by Loucks and van Beek in [36]. Let I represent the 'system performance indicator' which is the model output being observed while X is the model input parameter which is varied. The impact that an input parameter X has on the output I is given by the contribution its error variance ($Var[X_i]$) makes to the total error variance ($Var[I]$). (Error variance means the spread of the errors generated by the variability of parameter X. A small variance indicates that the estimates are close to the mean and thus have small standard deviation, which is simply the square root of the variance, and thus the estimates have high precision.) In other words:

$$\% = 100 \cdot \frac{Var[X_i]}{Var[I]} \tag{J-1}$$

Table J-1: Knowledge uncertainty parameter ranges

Parameter	Unit	Mean	St. dev	Min	Max	Condition
Specific impulse correction factor	[−]	0.9000	0.0192	0.8684	0.9316	none
Thrust chamber mass correction factor	[−]	1.52	0.80	0.204	2.836	none
Gas generator mass correction factor	[−]	1.52	0.80	0.204	2.836	none
Propellant tank performance factor	[−]	33200	10400	16092	50308	none
Pressurant tank performance factor	[−]	122000	39100	57680.5	186319.5	none
Dry mass correction factor	[−]	2.53	1.44	0.1612	4.8988	none

where

$$Var[I] = \sum \left[\left(\frac{\delta I}{\delta X_i} \right)^2 \cdot Var[X_i] \right] \tag{J-2}$$

with $\frac{\delta I}{\delta X_i}$ is the sensitivity coefficient which can be approximated by:

$$\frac{\delta I}{\delta X_i} = \frac{I_{i,high} - I_{i,low}}{X_{i,high} - X_{i,low}} \tag{J-3}$$

and the variance of parameter X is the square of the parameter's standard deviation:

$$Var[X] = (\sigma[X])^2 \tag{J-4}$$

once the total error variance is known, the total parameter standard deviation follows from the square root:

$$\sigma[I] = \sqrt{Var[I]} \tag{J-5}$$

The lower and higher value for parameter X (X_{low} and X_{high}) and its standard deviation ($\sigma[x]$) are found in Table J-1 and Table J-2.

J-1 Application to the Decision Uncertainty Parameters

For the computations test cased based on the Aestus engine for the pressure fed cycle, HM7B engine for the gas generator cycle, LE-7 engine for the staged combustion cycle , RL10A-3-3A for the closed expander cycle and LE-5A engine for bleed expander cycle, are used. Input data used is given in Table **??**. Some of this input data is hence not fixed but varied during the computations. All not shown input data such as pressurant choice, pressurant initial temperature, pressurant initial pressure, etcetera are assumed to have the typical values; these typical values are assumed automatically when LiRA is ran and no value is specified in the input file.

Change in velocity.

Table J-4 shows the sensitivity of the change in velocity to variation in the decision parameters for the gas generator test case.

Table J-2: Decision sensitivity parameter ranges

Parameter	Unit	Min	Max	Condition
Main comb. chamber pressure	[bar]	5	25	pressure fed
		5	105	gas generator
		10	70	expander
		70	210	staged combustion
Main comb. chamber mix. ratio	[−]	2.0	4.0	LOX-RP1
		3.0	7.0	LOX-LH2
		2.37	3.0	N2O4-MMH
Nozzle exit diameter	[m]	1	5	none
Nozzle area ratio	[−]	8	300	none
Atmospheric pressure	[bar]	0	1.01325	none
Burn time	[s]	100	1500	none
Pressurant initial pressure	[bar]	150	331	none
MEOP oxidiser tank	[bar]	13.0	90.0	pressure fed
		1.1	3.4	turbo-pump fed
MEOP fuel tank	[bar]	13.0	90.0	pressure fed
		1.1	3.4	turbo-pump fed
Pump efficiency	[−]	0.585	0.795	none
Turbine efficiency	[−]	0.345	0.723	none
Turbine mechanical efficiency	[−]	0.65	0.975	none
Turbine pressure ratio	[−]	1.85	22.0	none
Turbine inlet temperature	[K]	800	1350	none

Table J-3: Input used for study of sensitivity of change in velocity, thrust-to-weight-ratio and total wet mass to selected decision parameters

Parameter	Unit	pf	gg	sc	ce	be
Oxidiser	[−]	N2O4	LOX	LOX	LOX	LOX
Fuel	[−]	MMH	LH2	LH2	LH2	LH2
Nozzle exit diameter	[m]	1.315	0.992	1.737	1.02	1.625
Nozzle area ratio	[−]	84	82.9	52	61.1	130
Atmospheric pressure	[Pa]	0	0	0	0	0
Burn time	[s]	531	970	346	600	400
Pressure main combustion chamber	[bar]	11	36	131.7	32.6	39.8
Mixture ratio main combustion chamber	[−]	1.9	4.565	6.0	5.0	5.0
Nozzle cooling	[−]	No cooling	No cooling	No cooling	Regenerative cooling	Regenerative cooling
Chamber cooling	[−]	No cooling	Regenerative cooling	No cooling	Regenerative cooling	Regenerative cooling
Number of turbines	[−]	N/A	1	1	1	2
Engine throttle	[−]	No	Yes	Yes	Yes	Yes

pf: pressure fed cycle — gg: gas generator cycle
sc: staged combustion cycle — ce: closed expander cycle
be: bleed expander cycle — N/A: Not Applicable

Table J-4: Calculation of approximate parameter sensitivity regarding total wet mass

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Main combustion chamber pressure	9189.75	9116.93	-7.28E-06	486.944	0.1
Main combustion chamber mixture ratio	8304.86	9393.06	272.052	108741	16.5
Nozzle exit diameter	9206.29	9482.81	67.4437	7021.37	1.1
Nozzle area ratio	7835.39	9588.05	5.96142	282076	42.9
Pressurant initial pressure	9350.31	9261.45	-4.91E-06	725.028	0.1
MEOP oxidizer tank	9527.9	9022.66	-2.20E-03	23440.2	3.6
MEOP fuel tank	10474.8	8874.73	-0.00695682	235098	35.7
Pump efficiency	9210.72	9227.29	78.7285	25.3877	0.0
Turbine efficiency	9175.15	9226.71	136.259	245.544	0.0
Turbine mechanical efficiency	9201.01	9225.17	74.3229	53.5777	0.0
Turbine pressure ratio	9193.67	9226.14	1.865	96.8115	0.0
Turbine inlet temperature	9214.74	9239.03	0.0441619	54.1743	0.0

† parameter sensitivity

Table J-5: Calculation of approximate parameter sensitivity regarding total propulsion system volume

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Main combustion chamber pressure	0.405888	0.389403	-1.65E-09	2.50E-05	2.9
Main combustion chamber mixture ratio	0.384568	0.387443	0.000718867	7.59E-07	0.1
Nozzle exit diameter	0.403513	0.406813	0.000804848	1.00E-06	0.1
Nozzle area ratio	0.334321	0.426429	0.000313294	0.00077906	91.5
Pressurant initial pressure	0.405356	0.404225	-6.25E-11	1.17E-07	0.0
MEOP oxidizer tank	0.407553	0.400901	-2.89E-08	4.06E-06	0.5
MEOP fuel tank	0.417896	0.398861	-8.28E-08	3.33E-05	3.9
Pump efficiency	0.401791	0.40404	1.07E-02	4.67E-07	0.1
Turbine efficiency	0.396939	0.403961	0.01856	4.56E-06	0.5
Turbine mechanical efficiency	0.400471	0.403752	0.010096	9.89E-07	0.1
Turbine pressure ratio	0.39947	0.403884	0.000253523	1.79E-06	0.2
Turbine inlet temperature	0.403602	0.403776	3.16E-07	2.77E-09	0.0

† parameter sensitivity

Table J-6: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Main combustion chamber pressure	2175.21	47035.6	0.00448604	1.85E+08	1.0
Main combustion chamber mixture ratio	15945.5	16479.4	133.484	26178.9	0.0
Nozzle exit diameter	12897.7	399532	94301	1.37E+10	76.2
Nozzle area ratio	216004	4358.07	-719.883	4.11E+09	22.8
Pressurant initial pressure	15596.4	15640	2.41E-06	1.75E+02	0.0
MEOP oxidizer tank	15512.3	15769.7	1.12E-03	6084.28	0.0
MEOP fuel tank	15128.4	15850.4	0.003139	47864.2	0.0
Pump efficiency	15734.8	15647.2	-415.932	708.606	0.0
Turbine efficiency	15927.1	15650.3	-731.773	7081.87	0.0
Turbine mechanical efficiency	15786.7	15658.4	-394.754	1511.44	0.0
Turbine pressure ratio	15826.2	15653.3	-9.9343	2746.91	0.0
Turbine inlet temperature	15664.2	15657.5	-0.0122414	4.16254	0.0

† parameter sensitivity

Total propulsion system thrust-to-weight ratio

Table J-5 shows the sensitivity of the trust-to-weight ratio to variation in the decision parameters for the gas generator test case.

Total propulsion system wet mass.

Table J-6 shows the sensitivity of the total propulsion system wet mass to variation in the decision parameters for the gas generator test case.

J-2 Application to the Knowledge Uncertainty Parameters

The optimised propulsion system with a gas generator cycle is used as example. The requirements and fixed inputs used are shown in Table J-7

The results of the analysis are given in Table J-8 till Table J-16.

Main combustion chamber pressure

J-8 shows the sensitivity of the optimised main combustion chamber pressure to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Main combustion chamber mixture ratio

J-9 shows the sensitivity of the optimised main combustion chamber mixture ratio to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Table J-7: Ariane 5 LiRA upperstage engine optimisation requirements and fixed inputs

Parameter	Unit	Engine cycle gg
Requirements		
Change in velocity	[m/s]	3403.4
Thrust-to-weight ratio	[–]	0.245
Payload mass	[kg]	8000.0
Fixed input		
Oxidiser choice	[–]	LOX
Fuel choice	[–]	LH2
Atmospheric pressure	[bar]	0.0
Regenerative nozzle cooling	[–]	No
Regenerative chamber cooling	[–]	No
Number of turbines	[–]	2
Mixture type gas generator	[–]	fuel rich
Engine throttle	[–]	Yes

Table J-8: Calculation of optimal main combustion chamber pressure sensitivity with respect to selected knowledge uncertainty parameters

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	1.78E+06	1.43E+06	-73875.3	1.13E+10	0.65
Specific impulse correction factor	2.99E+06	7.18E+06	6.63E+07	1.62E+12	92.51
Propellant tank performance factor	4.41E+06	3.28E+06	-33.1967	1.19E+11	6.80
Pressurant tank performance factor	5.53E+06	5.44E+06	-0.671852	6.90E+08	0.04

† parameter sensitivity

Table J-9: Calculation of approximate parameter sensitivity regarding total propulsion system volume

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	4.34521	4.83042	0.102417	0.0217506	4.78
Specific impulse correction factor	4.41045	3.78084	-9.96715	0.0366222	8.05
Propellant tank performance factor	6.06687	4.08619	-5.79E-05	0.362441	79.67
Pressurant tank performance factor	5.369	5.9768	4.72E-06	0.0341297	7.50

† parameter sensitivity

Table J-10: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	1.98216	2.50502	0.110364	0.0252567	37.37
Specific impulse correction factor	1.85085	1.18382	-10.5596	0.0411054	60.82
Propellant tank performance factor	1.53801	1.5052	-9.59E-07	9.95E-05	0.15
Pressurant tank performance factor	1.37374	1.26329	-8.59E-07	0.00112702	1.67

† parameter sensitivity

Table J-11: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	266.104	252.813	-2.80538	16.3195	13.76
Specific impulse correction factor	253.739	275.214	339.965	42.6059	35.91
Propellant tank performance factor	250.484	225.173	-0.000739718	59.1832	49.89
Pressurant tank performance factor	280.982	278.598	-1.85E-05	0.525045	0.44

† parameter sensitivity

Nozzle exit diameter.

J-10 shows the sensitivity of the optimised nozzle exit diameter to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Nozzle area ratio.

J-11 shows the sensitivity of the optimised nozzle area ratio to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Thrust.

J-12 shows the sensitivity of the required thrust to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Burn time.

J-13 shows the sensitivity of the required burn time to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Table J-12: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	40379.3	54731.9	3029.52	1.90E+07	39.44
Specific impulse correction factor	59565.3	57310.9	-35689.4	469548	0.97
Propellant tank performance factor	66637.1	51710.8	-0.436238	2.06E+07	42.65
Pressurant tank performance factor	59477.9	50071	-0.0731257	8.18E+06	16.94

† parameter sensitivity

Table J-13: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	990	1000	2.11077	9.23864	16.67
Specific impulse correction factor	990	980	-158.308	9.23864	16.67
Propellant tank performance factor	1000	1000	0	0	0.00
Pressurant tank performance factor	950	970	0.000155474	36.9546	66.67

† parameter sensitivity

Total dry mass incl. payload.

J-14 shows the sensitivity of the total wet mass inclusive payload of the optimised stage to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Total wet mass incl. payload.

J-15 shows the sensitivity of the total wet mass inclusive payload of the optimised stage to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Table J-14: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	8081.47	11187.9	655.689	891499	44.46
Specific impulse correction factor	11806.3	11951.6	2299.91	1949.95	0.10
Propellant tank performance factor	13705.4	10692.6	-0.0880514	838570	41.82
Pressurant tank performance factor	11748.1	10028.5	-0.0133678	273197	13.62

† parameter sensitivity

Table J-15: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
dry mass correction factor	16588.3	22928.5	1338.29	3.71E+06	41.87
specific impulse correction factor	24982.7	24003.6	-15500	88566.1	1.00
propellant tank performance factor	28176	21525.5	-0.194367	4.09E+06	46.06
pressurant tank performance factor	23805.7	20544.8	-0.0253492	982385	11.07

† parameter sensitivity

Table J-16: Calculation of approximate parameter sensitivity regarding vacuum thrust

X	$I_{i,low}$	$I_{i,high}$	$\frac{\delta I}{\delta X}$	$\left(\frac{\delta I}{\delta X_i}\right)^2 \cdot Var[X_i]$	[%]†
Dry mass correction factor	32.6603	42.1249	1.99776	8.27586	55.68
Specific impulse correction factor	50.1644	51.6209	23.0578	0.195992	1.32
Propellant tank performance factor	46.829	43.189	-0.000106383	1.22408	8.23
Pressurant tank performance factor	42.403	34.9234	-5.81E-05	5.16849	34.77

† parameter sensitivity

Total propulsion system volume.

J-16 shows the sensitivity of the total propulsion system volume of the optimised stage to the uncertainty in the knowledge uncertainty parameters for a given and fixed change in velocity requirement of 3403.4 m/s, thrust-to-weight ratio of 0.245 and payload mass of 8000 kg.

Appendix K

LiRA User Manual

LiRA has three operation modes, the first one being normal engine analysis where a single engine cycle is completely analysed. The second mode is the optimisation routine which optimises several engine cycles for a given set of constraints. The last mode is uncertainty and sensitivity analysis which either performs an one-at-the-time first order sensitivity analysis for a given engine (cycle) or a simple Monte Carlo sensitivity analysis.

K-1 Normal engine analysis

- **Input file(s): engine definition file to be created in .../LiRA_v1.0/Input/Engines/**
- **Output file(s): none**

Step 1: Create Engine definition file

To start the normal engine analysis first create an engine definition file in the directory .../LiRA_v1.0/Input/Engines/ This file has to be made in ASCII text format using a certain structure; **the first 11 lines are available for comments and are not read into Matlab**. Everything starting from line 12 onwards is read.

Data is to be written in three tab delimited columns where the first column is the parameter number, the second parameter name and third parameter value. All values must be written in SI units. The first 18 parameters are the same in every engine independent of the engine cycle:

1. engine cycle (1: pressure fed, 2: gas generator, 3: staged combustion, 4: closed expander cycle, 5: bleed expander cycle) [-]
2. oxidizer (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]
3. fuel (1: LOX, 2: LH2, 3: N2O4, 4: MMH, 5: RP1) [-]
4. nozzle exit diameter [m]
5. nozzle arearatio (Ae/At) [-]
6. atmospheric pressure [Pa]
7. burn time [s]
8. pressure main combustion chamber [Pa]
9. mixture ratio main combustion chamber (O/F) [-]
10. nozzle cooling (1: none, 2: regenerative):
11. chamber cooling (1: none, 2: regenerative):
12. pressurant (1: He, 2: N2) [-]
13. pressurant initial temperature [K]
14. pressurant initial pressure [Pa]
15. oxidizer initial temperature [K]
16. fuel initial temperature [K]
17. combustion chamber wall material [-]
18. nozzle wall material [-]
19. engine throttled (1: yes, 2: no) [-]

The first 8 parameters are required input, all other parameters are optional and thus can be left without a value (hence an empty third column). It does not matter how the parameters are numbered or exactly named as long as a certain parameter is written on the intended line. For example parameter 17 is < combustion chamber wall material [-]> if the user desires he can also call it <mcc wall material [-]> or <Thomas> for that matter, as long as the main combustion chamber wall material parameter is defined as the 17th parameter in the file, LiRA will work correctly.

The other optional parameters are dependent on the engine cycle and the number of turbines.

In case of a **turbo pump fed** cycle the next 5 parameters (hence parameter 19 till 23) have to be:

20. Maximum Expected Operating Pressure oxidizer tank [Pa] <value>
21. Maximum Expected Operating Pressure fuel tank [Pa] <value>
22. oxidizer pump efficiency [-] <value>
23. fuel pump efficiency [-] <value>
24. number of turbines [-] <value>

The amount of turbines then determines the next parameters. For a **single turbine**, parameter 24 till 27 are:

25. turbine efficiency [-] <value>
26. turbine pressure ratio [-] <value>
27. turbine mechanical efficiency [-] <value>
28. maximum turbine inlet temperature [K] <value>

For a **double turbine** parameter 24 till 31 are:

25. oxidizer pump turbine efficiency [-] <value>
26. oxidizer pump turbine pressure ratio [-] <value>
27. oxidizer pump turbine mechanical efficiency [-] <value>
28. maximum oxidizer pump turbine inlet temperature [K] <value>
29. fuel pump turbine efficiency [-] <value>
30. fuel pump turbine pressure ratio [-] <value>
31. fuel pump turbine mechanical efficiency [-] <value>
32. maximum fuel pump turbine inlet temperature [K] <value>

In case a gas generator is present in the cycle, hence in the gas generator cycle and staged combustion cycle, the mixture ratio in the gas generator is the last parameter defined in the engie definition file.

For a **single turbine** gas generator or staged combustion cycle, this is the 28th parameter:

29. mixturetype gas generator (1: fuel rich, 2: oxygen rich) [-]: <value>

And for a **double turbine** generator or staged combustion cycle, this is the 32nd parameter:

33. mixturetype gas generator (1: fuel rich, 2: oxygen rich) [-]: <value>

The easiest way of defining your own engine definition file is copying one of the existing engine definition files and changing the values to the user needs. Of engine cycle and for every amount of turbines an real engine definition file already exists.

Step 2: Run main analysis routine

Run the Matlab file called <main.m> by either opening the file and pressing run in the editor or by going to the directory in the command window.

When running the user is first prompted in the command window to write the name of the engine definition file. For example for the HM7B a file HM7B.txt was created, hence to run the HM7B engine analysis write <HM7B> (without the extension .txt) in the command window. Next the user is prompted to ask if he or she desires to be asked for defining missing parameter values during analysis. If he or she does, type <Yes> and every time LiRA needs a value the user is suggested a typical value and asked if he or she would like to use this value or define one him or herself. If <No? was chosen typical values will be used automatically without prompting the user. All assumptions and typical values used are written to the command window, hence the user can see what values and assumptions LiRA has used.

No output is stored, the user has to select a variable or a structure at the side of the command window to see the values. Understanding of the engine cycle scheme component and line naming is essential. The main report shows how this works.

K-2 Optimisation

- **'constraints file' to be created in .../LiRA__v1.0/Input/optimisation/**
- **'optimisation results' located in .../LiRA__v1.0/Output/optimisation/**

Step 1: Create constraint file

The constraint file needs to be called <constraints.txt> and be located in a folder with the exact same name as the user want to name the project. Hence for example assume you want to name the optimisation project <test>, then you have to create a folder named <test> in the directory .../LiRA_v1.0/Input/optimisation/ and make a ASCII text file named <constraints.txt> inside. The constraint file itself needs to have a specified structure: **the first 11 lines are not read into Matlab and hence can be used for comments**. The next lines specify the constraints in 4 tab delimited columns where the first column contains the constraint name, the second the unit, the third the minimum bound value and the fourth the maximum bound value. Unlike the engine definition files the constraint names must be exactly the same every time. The unit must be SI bound values can be left open; if no minimum bound is specified -infinity is assumed, when no max bound is specified +infinity is assumed. The optimisation will always try to minimise mass for the given constraints, hence if no constraints are given the optimisation ends with the solution with the lowest mass that meets the requirements.

The structure of the constraint file must be as follows:

```
DeltaV [m/s] <value> <value>
Engine vacuum thrust [N] <value> <value>
Total wet mass [kg] <value> <value>
Total diameter [m] <value> <value>
Total length [m] <value> <value>
Total volume [m3] <value> <value>
L/d tanks [-] <value> <value>
```

Step 2: Run optimisation

Run the file named <main_optimization.m> to start the optimisation. The user is prompted for all kind of input which is self explanatory. For the project name be sure to name it exactly the same as the folder where the constraints file is located

Step 3: Inspect output files

The optimisation result is stored in a text file located in a folder with the same name as the project name (hence the same name as the folder where the constraint file is stored) located in the directory: .../LiRA_v1.0/Output/optimisation/

K-3 Uncertainty and Sensitivity analysis

For the uncertainty and sensitivity analysis the user has the choice to load an engine definition file and perform the analysis on the engine described in the file or the user can choose to perform the analysis for an continuously optimised system. In the latter a constraint file needs to be created and requirements need to be set.

K-3-1 For Non-fixed Requirements

- **'engine definition file' to be created in .../LiRA_v1.0/Input/Engines/**
  'constraints file' to be created in .../LiRA_v1.0/Input/optimisation/
- **sensitivity analysis results in .../LiRA_v1.0/Output/parameter sensitivity/**

Step 1: Create engine definition file

see procedure 'normal engine analysis'

Step 2: Run sensitivity analysis

Open and run <main_sensitivity_analysis.m>. The user is prompted for all kind of choices which are self-explanatory. The knowledge and decision parameters are described in the main report. The analysis method choices are one-at-the time (type <OAT> when prompted) or Monte Carlo (type <Monte Carlo> when prompted) . For the latter at least 100 samples should be used for a representative analysis. Monte Carlo analysis should only be conducted on the knowledge parameters as when attempting to run it on the decision parameters impossible (mostly negative) values for certain parameters can be generated due to the large standard deviation of some decision parameters.

Step 3: Inspect output files

The results are stored in following directory: .../LiRA_v1.0/Output/parameter sensitivity/ If the OAT analysis was chosen three files are created, one containing the results with respect to mass, one with respect to volume and the last with respect to thrust.

In case Monte Carlo analysis was chosen, a single file is stored, containing the input samples generated and the the results of the output parameters such as thrust, burn time, mass and volume.

K-3-2 For Fixed Requirements

- **'constraints file' to be created in .../LiRA_v1.0/Input/optimisation/**
- **sensitivity analysis results in .../LiRA_v1.0/Output/parameter sensitivity/**

Step 1: Create constraint file

see procedure 'optimisation'.

Step 2: Run sensitivity analysis

Open and run <main_sensitivity_analysis.m>. The user is prompted for all kind of choices which are self-explanatory. The knowledge and decision parameters are described in the main report. The analysis method choices are one-at-the time (type <OAT> when prompted) or Monte Carlo (type <Monte Carlo> when prompted). For the latter at least 200 samples should be used for a representative analysis, however 100 is suggested in case execution time is an issue. Monte Carlo analysis should only be conducted on the knowledge parameters as when attempting to run it on the decision parameters impossible (mostly negative) values for certain parameters can be generated due to the large standard deviation of some decision parameters. When asked for the amount of samples used in the optimisation 200 samples is recommended.

Step 3: Inspect output files

The results are stored in following directory: .../LiRA_v1.0/Output/parameter sensitivity/ If the OAT analysis was chosen three files are created, one containing the results with respect to mass, one with respect to volume and the last with respect to thrust.

In case Monte Carlo analysis was chosen, a single file is stored, containing the input samples generated and the results of the output parameters such as thrust, burn time, mass and volume.

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