Design of a supersonic business jet

A supersonic business jet (SBJ) design problem is used to demonstrate different analytical target cascading (ATC) formulations used for solving design problems involving multiple disciplines. The supersonic business jet design problem involves four subproblems; An overall **aircraft**, **propulsion**, **aerodynamics**, and **structural** design subproblems.

The `MATLAB` code that describes the inputs, outputs and underlying analyses for each subproblem is provided in the `NoHiMDO` code repository on `myCourses` inside the folder `SBJ`.

The individual `MATLAB` files for each subanalysis and their inputs and outputs are given in Table 1. The definition for each input and output is given in Table 2.

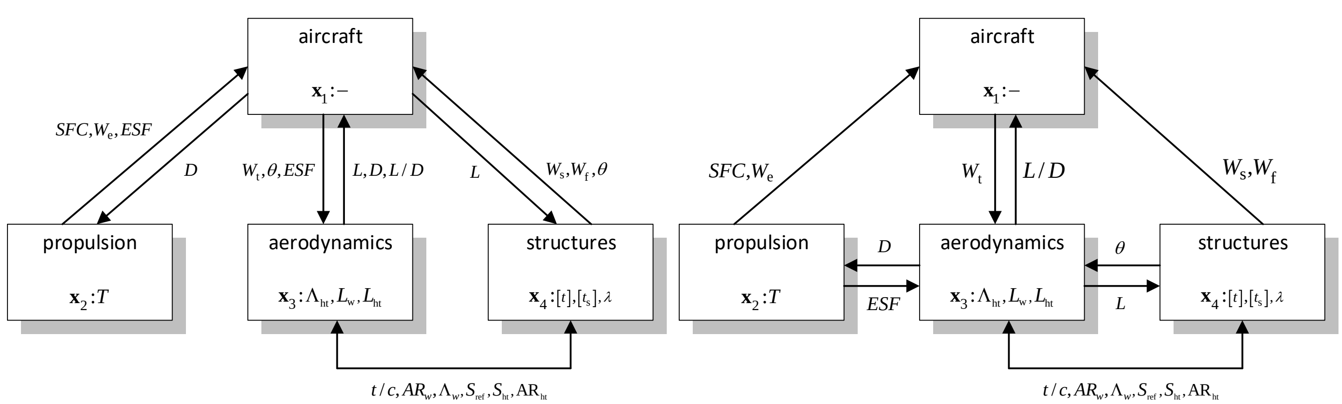
Based on these definitions, two possible formulations for a multidisciplinary design optimization (MDO) problem are provided. The objective is to minimize the total weight of the aircraft W_t given by subproblem 1.

Figure 1a describes an ATC formulation where subproblem 1 coordinates the solutions to the other 3 subproblems. There is no direct coupling between the individual subproblems. This is an example of a hierarchal ATC formulation.

Figure 1b describes an ATC formulation where the relevant inputs and outputs of each subproblem are directly coupled. This is an example of a non-hierarchal ATC formulation.

Table 1: Supersonic business jet subproblem definitions

Subproblem	**number**	**Inputs**	**Output**	`MATLAB` **file**
Aircraft	1	W_e, W_f, W_s, h, M, L/D, SFC	W_t, range	`SBJ_analysis_range.m`
Propulsion	2	h, M, T, D	SFC, W_e, ESF, T_E, Throttle	`SBJ_analysis_power.m`
Aerodynamics	3	t/c, h, M, AR_w, Λ_w, S_{ref}, S_{ht}, AR_{ht}, Λ_{ht}, L_w, L_{ht}, W_t, θ, ESF	L, D, L/D, P_g, CLo_1, CLo_2	`SBJ_analysis_dragpolar.m`
Structures	4	t/c, h, M, AR_w, Λ_w, S_{ref}, S_{ht}, AR_{ht}, $\mathbf{t}$, $\mathbf{t}_s$, λ, L	W_s, W_f, θ, $\mathbf{g}_1$	`SBJ_analysis_structural.m`



(a) ATC Formulation 1 (Hierarchical) (b) ATC Formulation 2 (Non-hierarchical)

Figure 1: ATC formulation of SBJ problem

Table 2: Supersonic business jet design variables

Variable	code designation	lower bound	upper bound	description
t/c	`tc`	0.01	0.1	Thickness/chord
AR_{w}	`ARw`	2.5	8	Wing aspect ratio
Λ_{w}	`LAMBDAw`	40	70	Wing sweep angle
S_{ref}	`Sref`	200	800	Wing surface area
S_{ht}	`Sht`	50	148.9	Tail surface area
AR_{ht}	`ARht`	2.5	8.5	Tail aspect ratio
T	`T`	0.1	1.0	Thrust
Λ_{ht}	`LAMBDAht`	40	70	Tail sweep
L_{w}	`Lw`	0.01	0.2	Wing distance
L_{ht}	`Lht`	1	3.5	Tail distance
$\mathbf{t}$	`t`	0.1	4.0	Nine thicknesses
$\mathbf{t}_{\text{s}}$	`ts`	0.1	9.0	Nine thicknesses
λ	`lambda`	0.1	0.4	Taper ratio
L	`L`	5000	100000	Total lift
W_{e}	`We`	100	30000	Engine weight
W_{t}	`Wt`	5000	100000	Total weight
θ	`theta`	0.2	50	Wing twist
ESF	`ESF`	0.5	1.5	Engine scaling factor
D	`D`	1000	70000	Total drag
W_{f}	`Wf`	5000	100000	Fuel weight
L/D	`LD`	0.1	10	Lift/drag ratio
SFC	`SFC`	1	4	Specific fuel consumption
W_{s}	`Ws`	5000	100000	Structural weight
Used for defining constraints				
range	`range`			Aircraft range
T_{E}	`Temp_E`			Engine temperature
Throttle	`Throttle_uA`			Engine throttle setting
P_{g}	`Pg`			Pressure gradient
CLo_1	`CLo1`			Lift coefficient 1
CLo_2	`CLo2`			Lift coefficient 2
$\mathbf{g}_1$	`G1`			Structural constraints
Constants				
M	`M`	1.4		Aircraft mach number
h	`h`	55000		Cruising altitude

Project deliverables

1. Execute the hierarchal ATC formulation of the supersonic business jet problem by executing the matlab file `SBJ_main.m`
   (a) Record the objective value f, and maximum inconsistency ϵ_q.
   (b) Take a screenshot of the figure showing the progress of optimization.
   (c) Check `SBJ_subsystem_analysis_1.m` and `SBJ_problem_definition_1.m` located in the main directory. The comments and annotations here will help you understand how to define objectives, constraints, shared variables, and coupling variables for the `NoHiMOD` algorithm.
2. Execute the non-hierarchal ATC formulation of the supersonic business jet problem by uncommenting line 47 and commenting line 46 in `SBJ_main.m`.
   (a) Record the objective value f, and maximum inconsistency ϵ_q.
   (b) Take a screenshot of the figure showing the progress of optimization.

Table 3: NoHiMDO algorithmic parameters

Parameter	Default	Possible values	Description
`display`	true	true,false	verbosity
`w_scheme`	'median'	'median','max','normal','rank'	Update scheme
`constraints_cv`	true	true,false	Penalty if coupling variables out of bounds
`realistic_obj`	false	true,false	Realistic objective
`inc_stop`	1e-12	real number > 0	Algo stops if this inconsistency is reached
`tol`	1e-12	real number > 0	Stop criteria on psize
`noprogress_stop`	100	integer > 1	Algo stops if the inconsistency has not decreased this number of iterations
`NI`	100	integer > 1	Number of inner loop iterations
`NO`	100	integer > 1	Number of outer loop iterations
`beta`	2	real number > 0	Hyper-parameter of the penalty update scheme
`gamma`	0.5	real number > 0	Hyper-parameter of the penalty update scheme
`w0`	1	real number $> 0, < 1$	Initial value for the w vector
`x0`	[]	vector of real numbers $> 0, < 1$	Initial design
`nb_proc`	1	integer > 0	Number of processors (requires MATLAB parallel computing toolbox)
`save_subproblems`	false	true,false	Save detail of each subproblem
`solver`	'mads'	'mads','sqp','interior-point','active-set','trust-region-reflective'	Solver
`solver_display`	false	true,false	Solver display

3. Comment on the difference in performance between the two formulations. Note and compare the number of iterations it took for the maximum inconsistency and objective values to stabilize.

4. Based on your observations from solving the hierarchal and non-hierarchal problems, provide an analogy in terms of management style that you may have observed in the industry (during an internship) and describe which one is potentially more efficient for reducing lead times of complex engineering products.

5. Formulate at least one more problem based on the supersonic business jet analyses.

   (a) Create a diagram showing the flow of the analysis variables between the different disciplines (similar to Figures 1a and 1b).

   (b) Mathematically express your formulation of the problem by writing down the optimization problems to be solved by each discipline (hint check the appendix of [1, 2] for example formulations). Be sure to describe

   - the objectives,
   - constraints,
   - variables to be optimized,
   - and inconsistencies to be coordinated by the problem.

   (c) Define new `SBJ_subsystem_analysis_x.m` and `SBJ_problem_definition_x.m` files.

   (d) Solve your problem using `NoHiMDO` by executing `SBJ_main.m`

   (e) Record the objective value f, and maximum inconsistency ϵ_q.

(f) Take a screenshot of the figure showing the progress of optimization.

6. Comment on the performance of your formulation of the problem relative to the hierarchal and non-hierarchal formulations.

7. Adjust the algorithmic parameters of `NoHiMDO` given by Table 3 and solve all three (or more) formulations of the problem and comment on how the performance of the algorithm was affected by these changes. Select at least three parameters that you think are the most significant ones for improving the algorithm's performance.

References

[1] S. Tosserams, M. Kokkolaras, L. F. Etman, and J. E. Rooda, "A nonhierarchical formulation of analytical target cascading," *Journal of Mechanical Design, Transactions of the ASME*, vol. 132, no. 5, pp. 0 510 021–05 100 213, may 2010. doi: 10.1115/1.4001346. [Online]. Available: http://asmedigitalcollection.asme.org/mechanicaldesign/article-pdf/132/5/051002/5592908/051002{_}1.pdf

[2] B. Talgorn, M. Kokkolaras, A. DeBlois, and P. Piperni, "Numerical investigation of non-hierarchical coordination for distributed multidisciplinary design optimization with fixed computational budget," *Structural and Multidisciplinary Optimization*, vol. 55, no. 1, pp. 205–220, 2017. doi: 10.1007/s00158-016-1489-z