MULTI DISCIPLINARY OPTIMIZATION OF RAILWAYS SYSTEMS

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Abstract

After an analysis of the design process of railway structures, we set up a formulation for the multi-disciplinary optimization of a rail body structure. The optimization takes into account several disciplines (static and vibratory structural analysis, crash, fire resistance, comfort), integrating engineering design as well as regulation criteria.

The proposed methodology is used to compare different strategy of optimization and to show the interest of taking into account several disciplines in order to achieve cost-effective design.

Introduction

In this paper, we propose an original formulation of Multi Discipline Optimization (MDO) for railway rolling stocks. The application is the design of a new generation subway rail car. This paper presents the results of preliminary work where no operational applications are carried out. However, we present several concrete examples taken from ALSTOM design practice.

In particular, we have developed a demonstrator, which formulates and solves a simplified version of the MDO problem for railway structural systems.

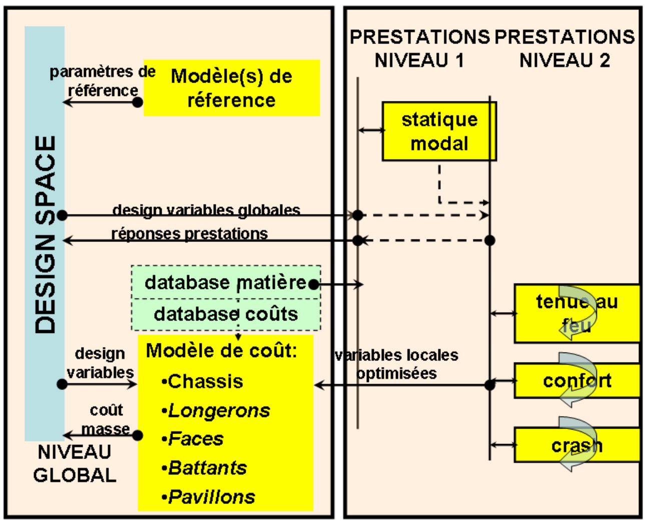
First, we identify the different disciplines relevant to the design of such systems. Then, we study the coupling and the hierarchical dependence of such disciplines, so to formalize the design process used by ALSTOM for its subway car bodies.

Finally, we have coupled this design procedure with an architectural model of the body. This has enabled us to use the body cost as well as the mass as optimization responses.

In the present study, we have taken into account four disciplines :

- Structures (static, vibration)
- Fire heat resistance
- Comfort
- Crash

A demonstration program plays the MDO design point and show the influence of the different disciplines and the interactions thereof.



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accepted for publication, IDDME 2010

The engineering problem

We recall the disciplines which we have considered for the purpose of our study:

- Structural mechanics (static, vibration). Fatigue resistance has also been taken into account but it is not presented here.
- Fire heat resistance.
- Comfort.
- Crash.

The interaction of the different disciplines will be investigated in a following chapter. However, it is important at this point to know that structural mechanics sets up a number of parameters for the other disciplines. It is therefore considered a "level 1" discipline, whereas the others are "level 2".

Two objective functions have been taken into account:

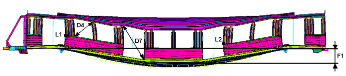
- Mass
- Cost

Mechanics (static, modal)

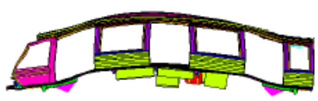
Based on the EN_12663-1 (CEN/TC, 2007), directive, we consider three load cases with the relative responses :

- Deflection on rail for the vertical overload (VOL / 12EL10)
- 100 ton compression in the x-direction
- First vibrational frequency in modal analysis

VOL



frequency



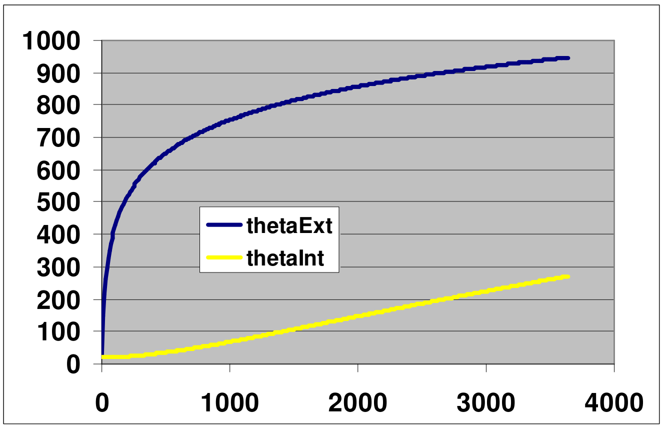
compression

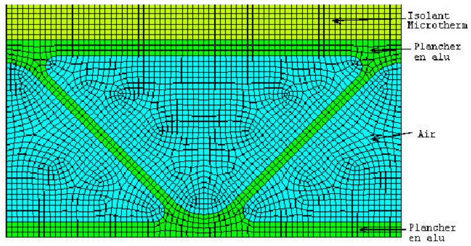
Fire resistance (level 2)

Fire underneath chassis (ALSTOM, 2005) is modeled via a temperature rise underneath (θ_{ext}). We want to control the temperature (θ_{int}). inside the vehicle (opposite side of the chassis).

To model this load case, we add to the structural design variables (which, as we shall see, will not change) a specific design variable representing the thickness of the thermal protection layer.

The value of this design variable is identified using an optimization and used for the computation of mass and cost.





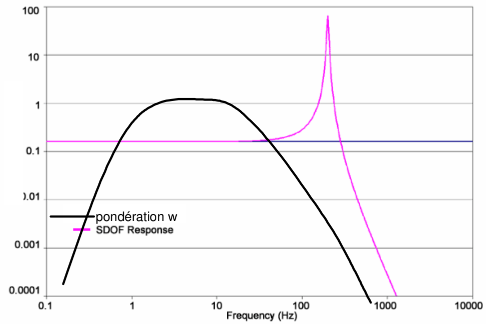
Responses

N	Name	Variables	Title	Select	Visible
1	vertOve...	18.900597	vertOverLongitudinalDeflection	✓	✓
2	firstFle...	8.499663	firstFlexFrequency	✓	✓
3	deltaFr...	1.4996634	deltaFreqWithBogie	✓	✓
4	compr...	11.0	compressionEndDeflection	✓	✓
5	revete...	8.0	revetementPlancherThickness	✓	✓

Comfort (level 2)

Comfort assessment is based on the comfort index, as defined in ISO2631 (1985). It is obtained from the acceleration of a subset of points in the chassis after weighted integration in the frequency domain:

$$a_w = \sqrt{\int_0^\infty w^2(\omega) H^2(\omega)}$$



We start from structural mechanics (level 1) responses:

- Modal frequencies
- Modal damping

And we add a level 2 variable:

- Extra damping needed to reach the desired comfort index.

Responses

N	Name	Variables	Title
1	vertOve...	18.900597	vertOverLongitudinalDeflection
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3	deltaFr...	1.4996634	deltaFreqWithBogie
4	compr...	11.0	compressionEndDeflection
5	structu...	0.019993665	structuralDamping
6	comfor...	0.0028367...	comfortAw
7	csiCo...	0.037508424	csiComfort

The value of this design variable is identified using an optimization and used for the computation of mass and cost.

Crash (level 2)

Following CEN/TC 256 (2007), we consider the impact between two subway trains at 25 Km/h.

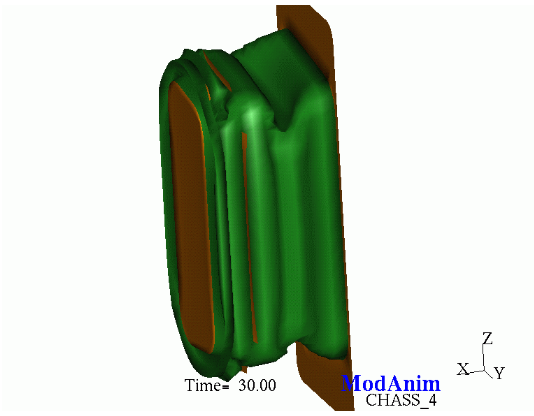
Starting from the body defined in the structural mechanics model, we want to control:

- Maximum acceleration during impact
- Body deformation, in particular the end deflection.

We add some level 2 variables:

- Absorber resistance (force)
- Absorber maximum deformation (length)

The values of these design variables are identified using an optimization and used for the computation of mass and cost.



Formulation of the optimization problem

As in every problem of optimization, we must identify:

- The design variables with their domain of variability
- The responses, which can originate:
  - Constraints
  - Objectives

We call a design point the set of design variables and of the responses for a given configuration.

In a MDO context, each discipline carries its own design variables and responses. When two disciplines share the same variable, we say that the coupling between them is strong. Otherwise, we call it weak coupling.

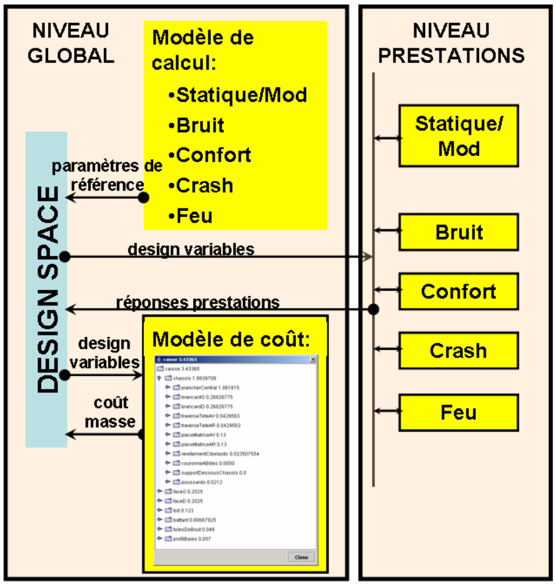
The actual choice of the optimization algorithm is secondary and it is determined both by the formulation and by the computational facilities available.

Parallel approach

In a parallel approach, all disciplines contribute to the computation of responses, and the design variables are all the parameters defining the system. For each design point, we carry out all the performance computation.

Hence, we solve an optimization problem with a large number of design variables and responses.

This approach is conceptually simple but it proves itself unfeasible for industrial design problems.

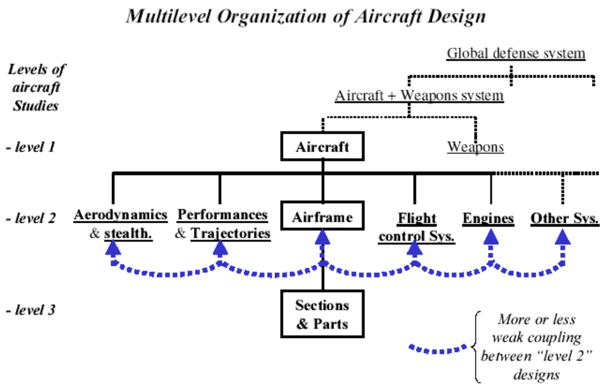


Hierarchical approach

Several such approaches have been proposed in different industrial domains. The principle is to break up the complex parallel problem outlined above, by a separate optimization of the different performances.

The aerospace industry (cfr. For example Sobieski, 1993, Petiau et al, 2006) has used the hierarchical approach for a long time. The optimization problem is split up in several levels, and in each level the disciplines have a weak coupling.

The optimal set of design variables for the upper level becomes the objective/constraints responses for the lower level. At each level, disciplines are optimized separately.



(de Ch. Petiau et autres, 2006)

For instance, the optimization of several missions at aircraft level yields optimal values for drag and lift coefficients for airfoils. The latter are the responses of the optimal design problem for the airfoil at the lower level.

We should also point out that, in this context, Clients and regulating bodies do not set specific constraints on the performances.

In the case of rolling stock design, a purely hierarchical approach is not suitable, for two reasons:

- Different disciplines show a strong coupling

- Responses (performances) are often defined by the regulating bodies or otherwise specified by the customers

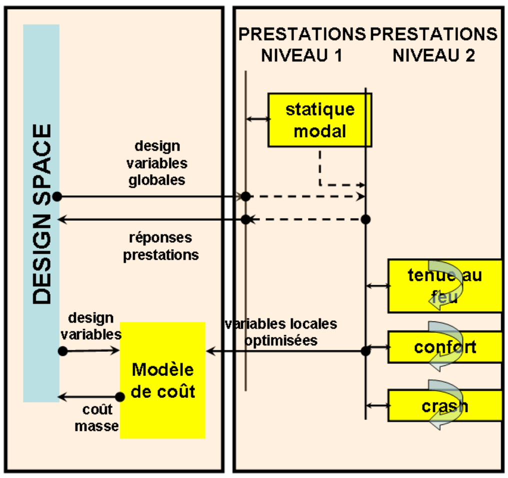
However, we can always try to solve the MDO problem via a sequence of simpler optimizations, by the following procedure:

- Study the design practice and identify a hierarchy of design
- Identify the global design variables and those specific to each discipline
- Identify the coupling between disciplines when it exists

Hierarchic approach for railway structures

We consider the following model of the design process:

1. Identification of mechanical performances (static, modal). This will be our level 1 discipline.
2. Design of crash absorbers using quasi-static simulations (weak coupling with mechanics).
3. Chassis fire resistance is studied to size up the fire protection layer (strong coupling with mechanics).
4. Comfort performance is assessed from modal characteristics of the body (strong coupling with mechanics). If necessary, additional damping systems are set up (weak coupling).



LOCAL OPTIMIZATION

Once we formalize this procedure, a design point is defined as :

- A simulation for level 1 discipline (mechanics)
- Local optimization for level 2 disciplines

In the local optimization, the design variables are those specific to the level 2 disciplines, whereas the level 1 variables do not change.

Mechanics (static, modal) is the level 1 discipline.

Level 2 disciplines are:

- Crash
- Comfort
- Fire resistance

Optimal values of local level 2 variables are taken into account at level 1 in two fashions:

- They contribute to the computation of the cost of the structure (objective function).
- They can be introduced as responses/constraints in the optimization (e.g. total chassis thickness and other architectural parameters).

Such a hierarchical model formalizes a particular design practice representative of ALSTOM process. For instance, when we consider the “comfort” performance, we assess it starting from a given modal model of the body, without modification of the level 1 variables. However, we can add specific damping feature to improve comfort. This leads to a cost increase which can penalize a design point and change the optimal solution.

Cost objective function

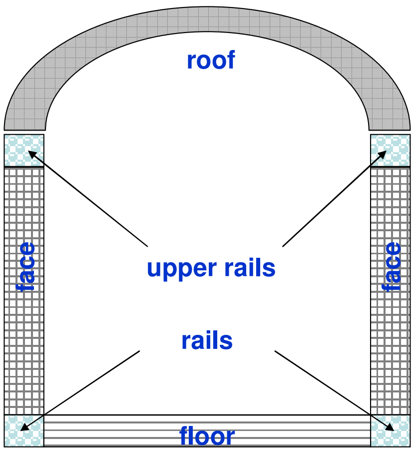
Besides the mass of the body, we use the production cost of the structure as objective function to minimize. It is defined using the following formula, taken into account the production cost of each component, plus the cost of assembly. Development cost is spread out over the number of bodies produced:

$$C_R = \sum_{i=composant} C_i + \sum_{\substack{i=composant \\ j=composant}} C^{ij}_{assemblage} + \frac{C_{développement}}{N_{caisses}}$$

Application to ALSTOM subway cars

Subway car case study

The application presented in this paper is the body optimization of the MP05 ALSTOM subway car body.



The transversal section of the structure is made up of five modules:

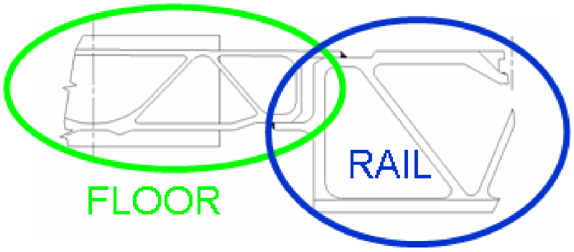
- Roof
- Upper rails
- Faces
- Rails
- Floor

the floor and the rails are commonly referred to as “chassis”

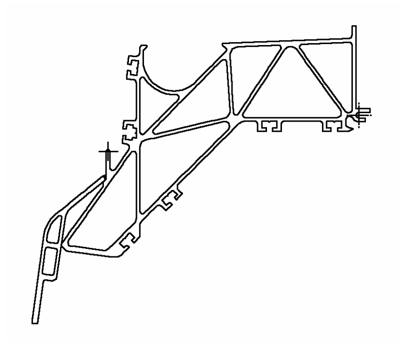
In this study, we concentrate on the sizing of the chassis and the upper rails. These parts are made up of extruded aluminum. Hence, they are defined by a section geometry and a rib thickness, which we consider homogeneous.

Five design variables are considered. Four of them are associated to the chassis components, namely:

- Floor height (sometimes referred to as thickness)
- Rail height or thickness
- Floor rib thickness
- Rail rib thickness



A fifth variable is associated to the rib thickness of the upper rail



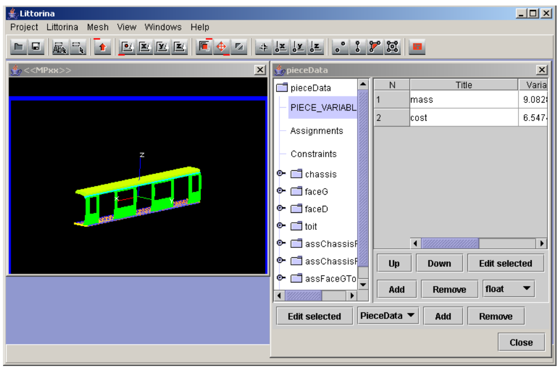
The structure is subjected to a number of design constraints related to its mechanical performance. In this study, we enforce three of them:

- Vertical overload rail deflection (19 mm maximum)
- 100 tons compression end deflection (11 mm maximum)
- First flexural frequency (8 Hz minimum)

Other local constraints are imposed on the level 2 disciplines.

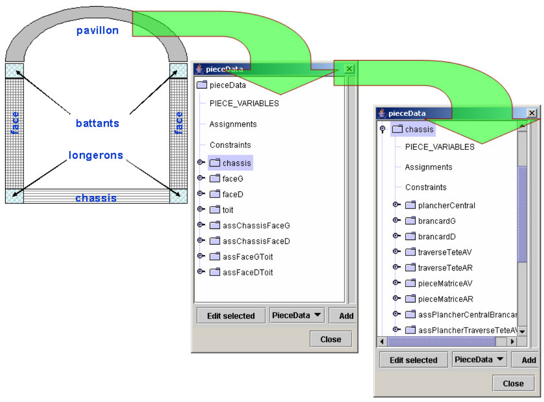
Formulation of the design point

In order to test the optimization procedure outlined above, the body architecture, cost model and physical behavior have been implemented in ***littorina***, custom software based on SimTech ENKIDOU™ library.



littorina plays an MDO design point. For optimization, it can use either ENKIDOU™ optimization algorithms or it can be coupled to a third party optimization engine.

The application includes an assembly database and a design space, handling the definition of design variables, responses and the interface with third party optimization engine.



MDO optimization for the subway car

We have carried out two optimizations on the MP5 aluminum design:

- A “classical” optimization, minimizing the mass of the structure using the mechanical constraints only
- A MDO optimization, where we minimize the cost of the structure, taking into account the level 2 disciplines. The mechanical constraints are always enforced.

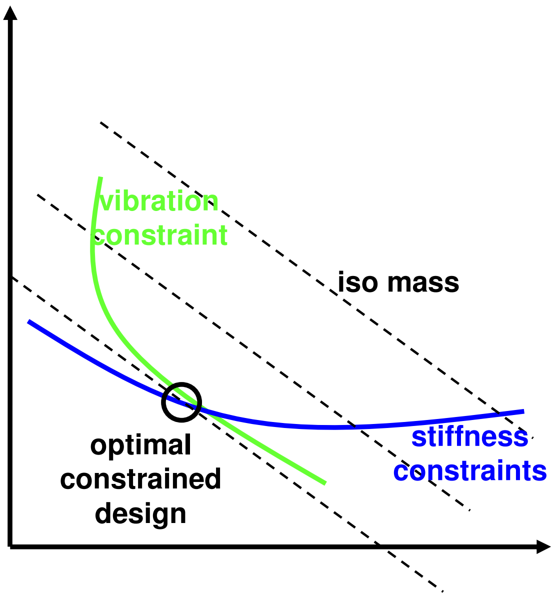
Due to the approximations in the model, the numerical values of the design variables and responses at the optimal points are not necessarily representative of the industrial design practice at ALSTOM. However, these optimizations prove the interest of integrating cost computation and several disciplines in the traditional design, based on structural mechanics.

Further, confidentiality issues prevent us from disclosing actual cost data for ALSTOM cars. Cost data presented have been altered and are just proportional to actual cost data.

The responses at the optimal point for the two optimizations are summarized in the following table:

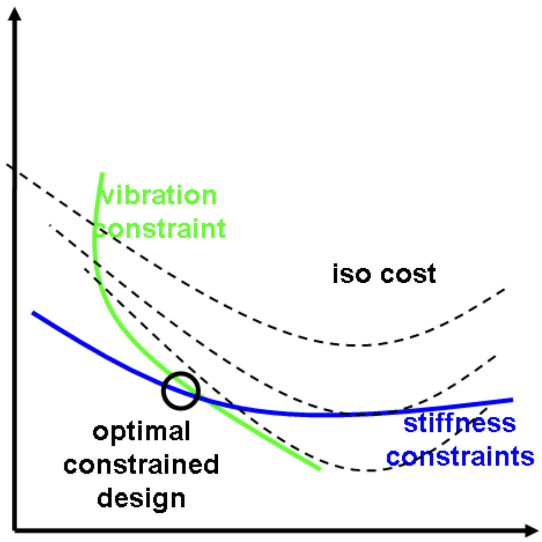
	Mass optimization		Cost MDO optimization	
Mass Kg	3259		3566	
Cost Euro (NB: dummy data)	105384		98795	
VOL rail deflection	19	(active)	15.4	(not active)
100 tons compression	11	(active)	11	(active)
First flexural frequency	8	(active)	8.8	(not active)

We point out that the constraints are all active in the first optimization (mass minimization under the constraints of structural mechanics). In this case, there is a constraint coming for each load case and no direct coupling between the constrained responses and the objective function. The Kuhn-Tucker conditions (see for instance Valderplaats, 1999) is met at a point where all the constraints reach their bound, in other words, they are all active at the optimal point.



We recall that level 2 variables do not affect the computation of the mechanical constraints but modify the objective function, thus leading to a different optimal design point. In the MDO optimization, the mechanical constraints are no longer all active. The most cost-effective solution is more conservative in terms of purely mechanical performances.

We can also point out that the optimal MDO design point, whilst significantly heavier than the design with minimum mass, has a lower cost.



In the latter design, even though the purely structural cost is lower, the cost of satisfying the level 2 performance requirements (fire, crash, comfort), is much higher.

The optimal set of design variables is significantly different in the two optimizations:

	Mass optimization	Cost MDO optimization
Rail thickness	118	150
Floor thickness	100	100
Upper rail rib thickness	7	10
Rail rib thickness	7	7
Floor rib thickness	8	7

Conclusions

We have shown the industrial feasibility of a Multi Disciplinary Optimization methodology, formalizing an actual industrial design process.

The overall financial cost of the structure is more significant a criterion than the mass, which is more often used as a design objective. Further, using the cost as an objective function, instead of the mass, we were able to take easily into account the effect of several disciplines in the design optimization.

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