


목 차

- 구조최적설계
- 위상최적설계
 - 정식화
 - 사례: 자동차 분야

구조최적설계: 개념

- 설계변수 (d)
 - 부재크기 (두께, 단면적, 길이), 경계 (절점/조절점 좌표)
 - 상태변수 (U)
 - 중량, 응력, 변위, 온도, 고유진동수, 좌굴하중
 - 목적함수, 제약조건
 - 결정사항
 - 해석 종류: 상/편 미분방정식
 - 설계 공간 (설계변수)
 - 목적함수 및 제약함수 (구조 거동, 구조 기하)
- 상태방정식
지배방정식
- 

구조최적설계: 설계변수

■ 치수 (Size)

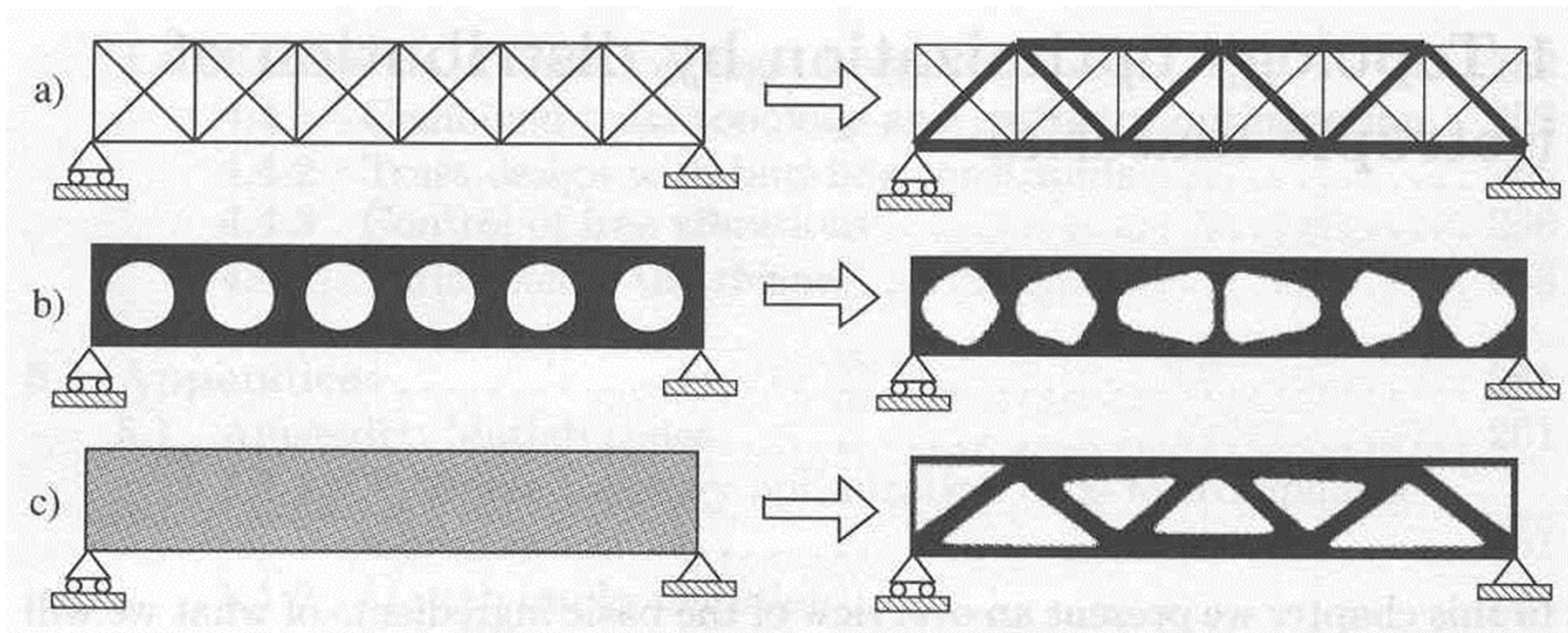
- 부재크기
- 두께, 단면적, 길이

■ 형상 (Shape)

- 경계
- 절점/조절점 좌표

■ 위상 (Topology)

- 재료 유/무
- 요소밀도



M.P.Bendsøe and O. Sigmund, Topology Optimization: Theory, Methods and Applications, Springer, 2003

구조최적설계: 정식화

- 설계변수 :
- 목적함수 : 부피(중량) 최소화
- 제약조건 : 상태방정식(해석), 최대응력, 최대변위



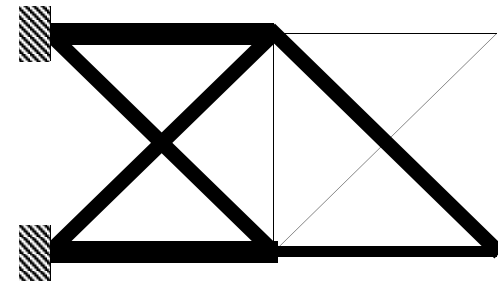
$$\min_d \int_{\Omega} \rho d\Omega$$

subject to

$$\begin{cases} a(\mathbf{u}, \mathbf{v}) = f(\mathbf{v}) \forall \mathbf{v} \\ \bar{\sigma} \leq \sigma_{\max} \\ |\mathbf{u}| \leq u_{\max} \end{cases}$$

■ 치수최적설계

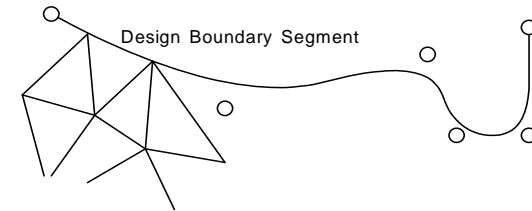
- 항공/토목 구조물: 트러스, 빔, 프레임
- 기계구조물: 형상과 관련



○ Control Points

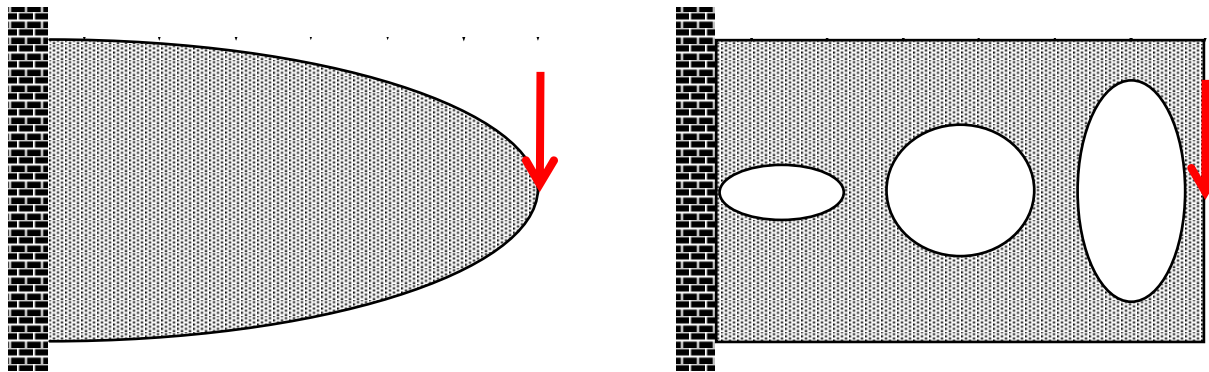
■ 형상최적설계

- 파라메트릭 기하 표현: 자동 요소망 생성 필요
- 기저형상 활용



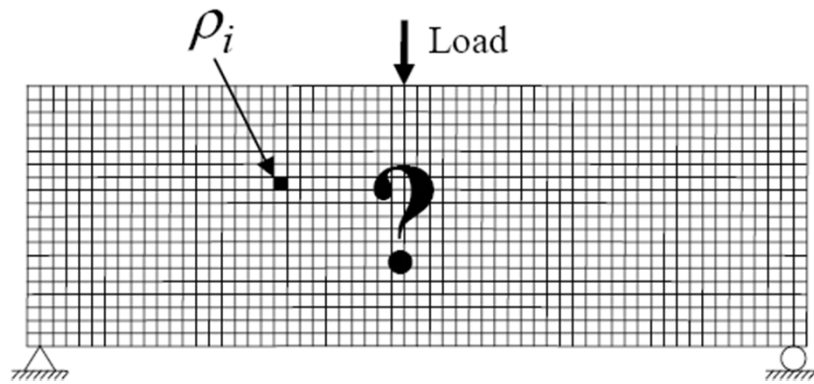
구조물 경량화

- 치수(size) 및 형상(shape) 최적설계
 - 초기설계에 크게 의존
 - 최적설계에 의한 경량화 효과 적음 (우수한 초기설계인 경우)
- 효과적인 구조물 경량화: 구조물 내 구멍 생성
 - 구멍의 위치/크기/형상: 패러다임 변화 필요
 - 위상(topology)최적설계 제안



새로운 패러다임: 위상최적설계

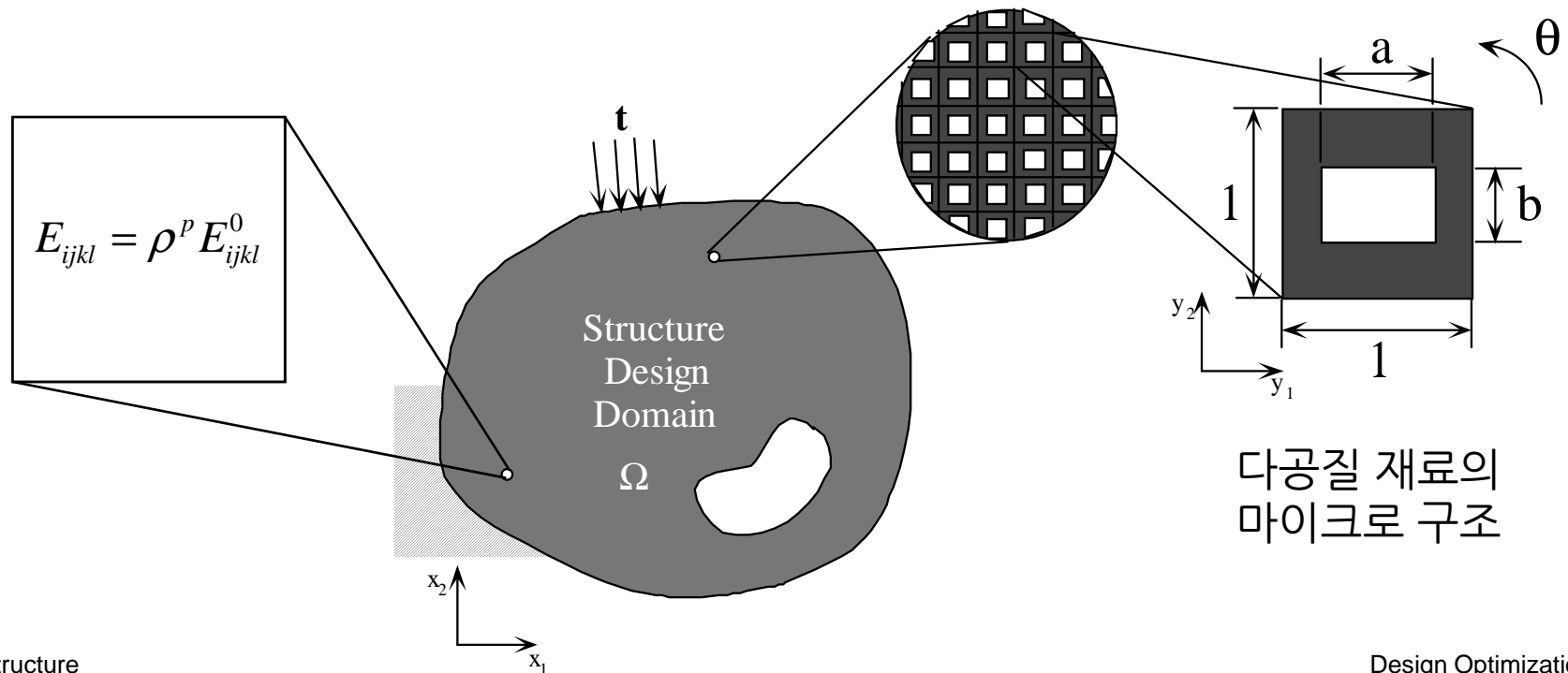
- 형상최적설계의 문제점
 - 형상변화에 따른 해석모델 재생성
 - 설계변화계산의 어려움, 제한적 형상변화
- 아이디어?
 - 해석모델 고정: 구조최적설계방법이 유한요소생성과 별개
 - 형상을 유한요소의 밀도로 표현(pixel, voxel 개념)



위상최적설계: 개념

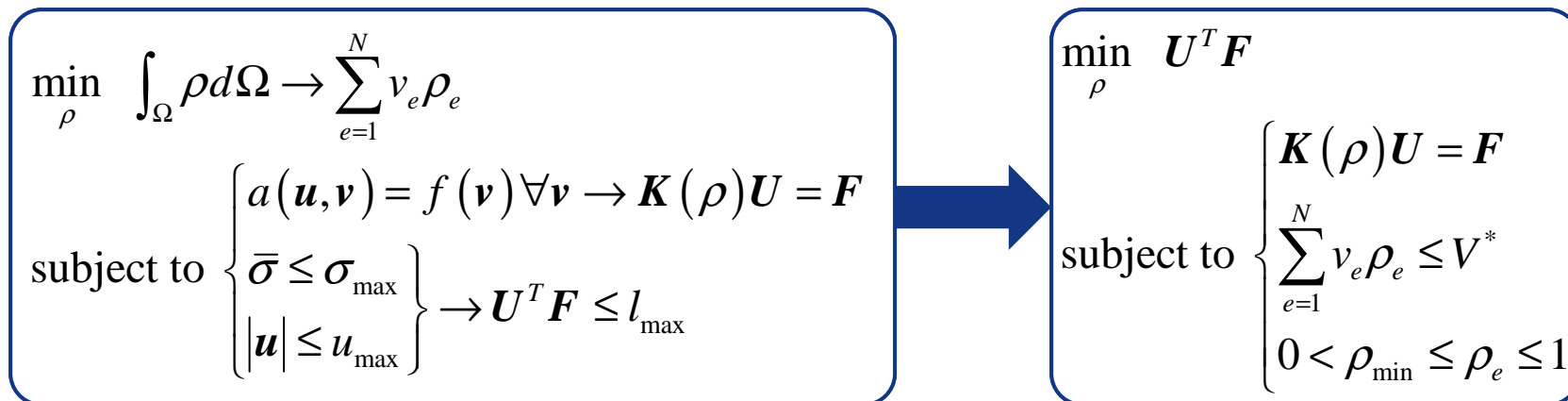
- 설계변수

- 구조물의 재료분포(탄성계수)를 표현하는 값
- 균질화설계법: 다공질구조로 모델링, 복합재역학이론으로 균질화된 물성 계산
- 밀도법: 유한요소의 밀도로 물성계산



위상최적설계: 정적 문제

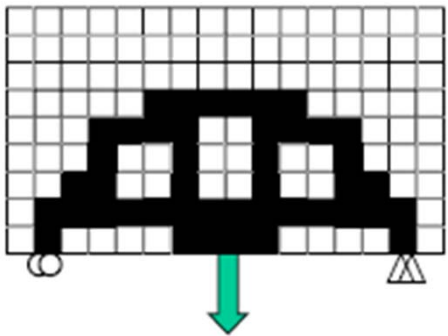
- 설계변수 (ρ)
 - 이산화한 각 유한요소의 밀도
- 문제 정식화
 - 부피 최소화, 응력/변위 제약조건: 주어진 강도/강성을 만족하는 경량화 설계
 - 응력: 트러스, 빔, 프레임 구조물에서는 유한값, 연속체에서는 국부적 물리량
 - 전역적 물리량 (평균컴플라이언스) 도입: 강성 표현



위상최적설계: 밀도법

■ 정수(0/1) 문제

- 모든 조합? Ill-conditioned



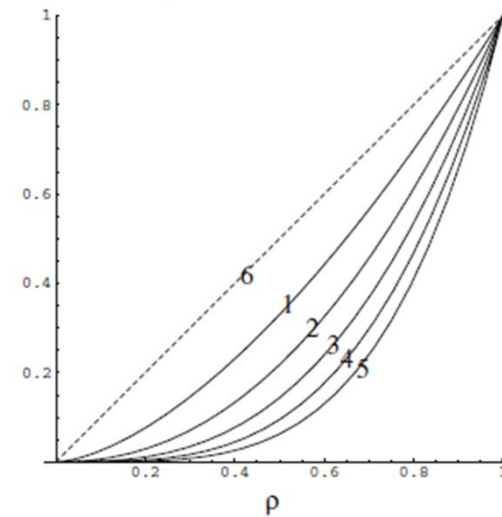
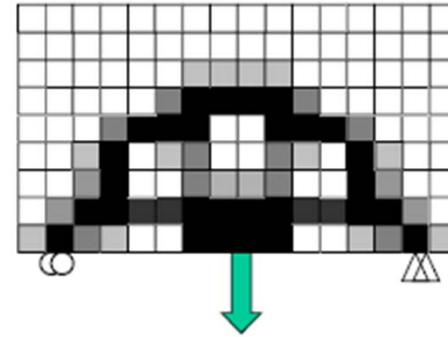
$$\min_{\rho} U^T F$$

$$\text{subject to } \begin{cases} K(\rho)U = F \\ \sum_{e=1}^N v_e \rho_e \leq V^* \\ 0 < \rho_{\min} \leq \rho_e \leq 1 \end{cases}$$

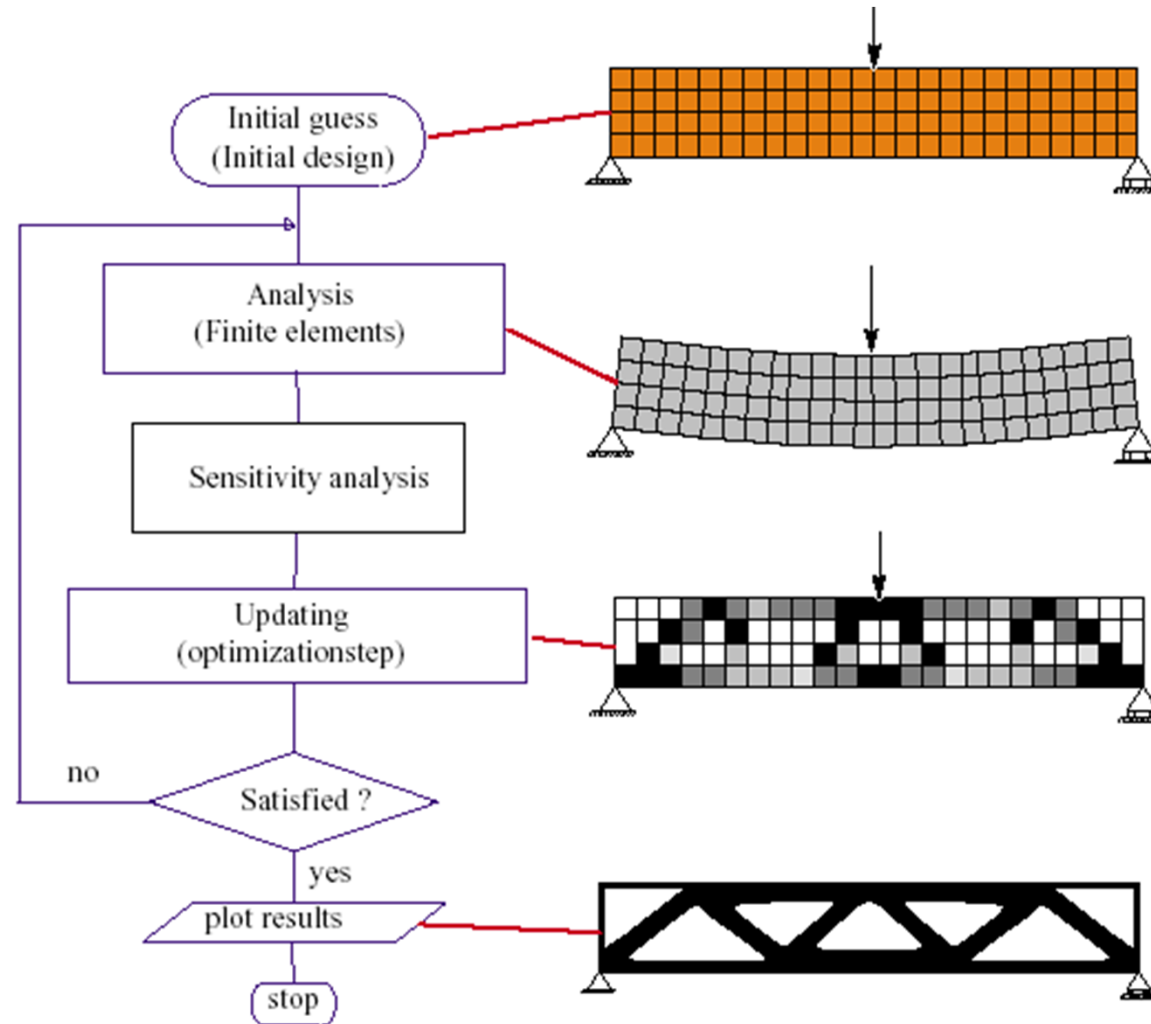
$$E(\rho_e) = \rho_e^p E_0 \\ p > 1$$

■ 실수(0~1) 문제

- 완화, 중간밀도?



위상최적설계: 흐름도



M.P.Bendsøe and O. Sigmund, Topology Optimization: Theory, Methods and Applications, Springer, 2003

Topology Optimization: Formulation

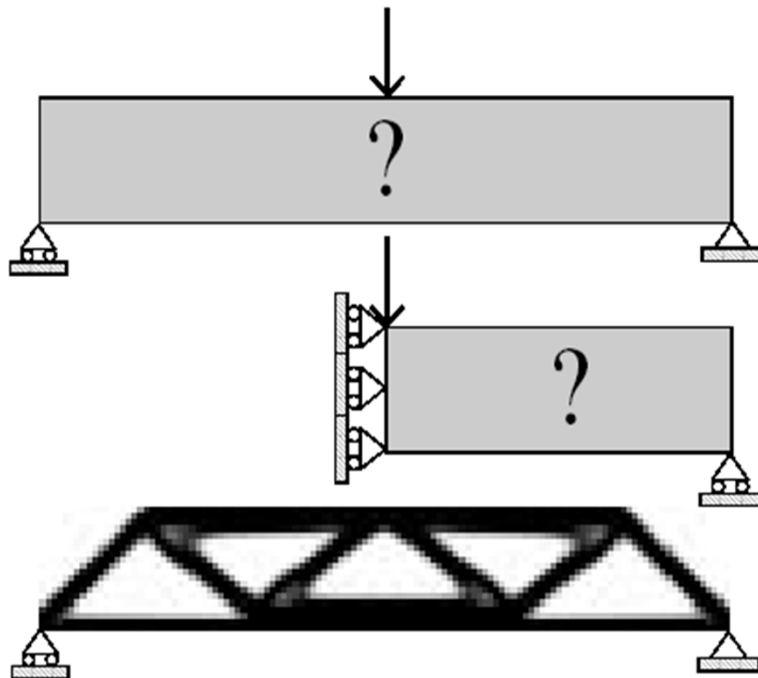
$$\left. \begin{array}{l} \min_{DV} \int_{\Omega} \rho d\Omega \rightarrow \sum_{e=1}^N v_e \rho_e \\ \text{subject to } a(\mathbf{u}, \mathbf{v}) = f(\mathbf{v}) \forall \mathbf{v} \rightarrow \mathbf{K}(\rho) \mathbf{U} = \mathbf{F} \\ \left. \begin{array}{l} \bar{\sigma} \leq \sigma_{\max} \\ |\mathbf{u}| \leq u_{\max} \end{array} \right\} \rightarrow \mathbf{u}^T \mathbf{f} \rightarrow \mathbf{U}^T \mathbf{F} \end{array} \right\} \xrightarrow[\substack{\text{dual problem} \\ E(\rho_e) = \rho_e^p E_0}]{} \left\{ \begin{array}{l} \min_{\rho} \mathbf{U}^T \mathbf{F} = \phi(\mathbf{U}(\rho)) \\ \mathbf{K}(\rho) \mathbf{U} = \mathbf{F} \\ \text{subject to } \left\{ \begin{array}{l} \sum_{e=1}^N v_e \rho_e \leq V^* \\ 0 < \rho_e \leq 1 \end{array} \right. \end{array} \right.$$

$$L(\rho, \mathbf{U}, \lambda, \Lambda, \lambda_e^-, \lambda_e^+) = \phi + \lambda^T (\mathbf{K}\mathbf{U} - \mathbf{F}) + \Lambda \left(\sum_{e=1}^N v_e \rho_e - V^* \right) + \sum_{e=1}^N \lambda_e^- (-\rho_e) + \sum_{e=1}^N \lambda_e^+ (\rho_e - 1)$$

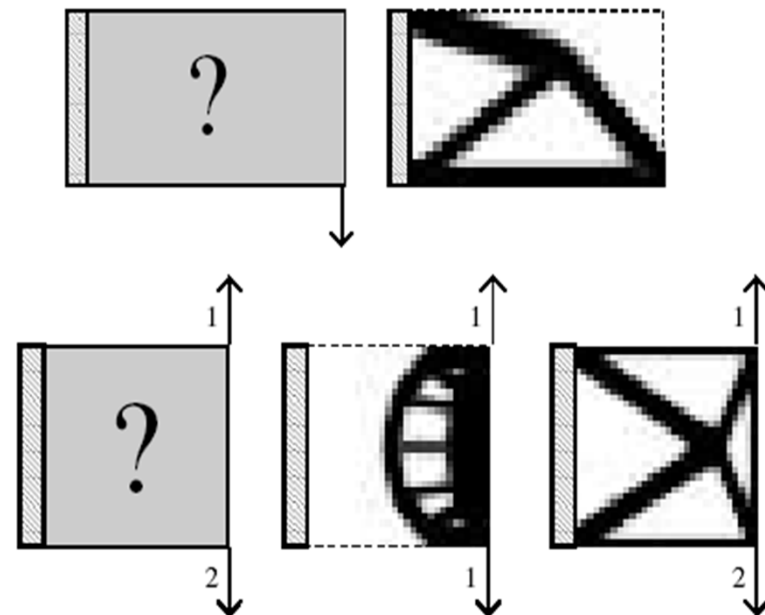
$$\left. \begin{array}{l} \frac{\partial L}{\partial \rho} = \frac{d\phi}{d\rho} + \frac{\partial \phi}{\partial \mathbf{U}} \frac{\partial \mathbf{U}}{\partial \rho} + \lambda^T \left(\frac{\partial \mathbf{K}}{\partial \rho} \mathbf{U} + \mathbf{K} \frac{\partial \mathbf{U}}{\partial \rho} - \frac{\partial \mathbf{F}}{\partial \rho} \right) + \Lambda v_e - \lambda_e^- + \lambda_e^+ = 0 \\ \frac{\partial L}{\partial \mathbf{U}} = \frac{\partial \phi}{\partial \mathbf{U}} + \lambda^T \mathbf{K} = 0 \rightarrow \mathbf{F} + \mathbf{K}^T \lambda = 0 \rightarrow \lambda = -\mathbf{U} \\ -\mathbf{U} \frac{\partial \mathbf{K}}{\partial \rho} \mathbf{U} \rightarrow -\mathbf{U}_e^T \frac{\partial \left(\sum_e \mathbf{K}_e \right)}{\partial \rho_e} \mathbf{U}_e = -\mathbf{U}_e^T (p \rho_e^{p-1} \mathbf{K}_e^0) \mathbf{U}_e \end{array} \right\} \rightarrow \left\{ \begin{array}{l} -\mathbf{U}_e^T (p \rho_e^{p-1} \mathbf{K}_e^0) \mathbf{U}_e + \Lambda v_e = 0 \\ 1 = \frac{\mathbf{U}_e^T (p \rho_e^{p-1} \mathbf{K}_e^0) \mathbf{U}_e}{\Lambda v_e} = B_e \\ \rho_e^{new} = \rho_e (B_e)^\eta \end{array} \right.$$

Educational Design Tool (1)

- TOPOPT (www.topopt.dtu.dk)
 - O. Sigmund, A 99 line topology optimization code written in Matlab, Struct Multidisc Optim 21, pp.120-127, 2001
 - D. Techerniak and O. Sigmund, A web-based topology optimization program, Struct Multidisc Optim 22, pp.179-187, 2001

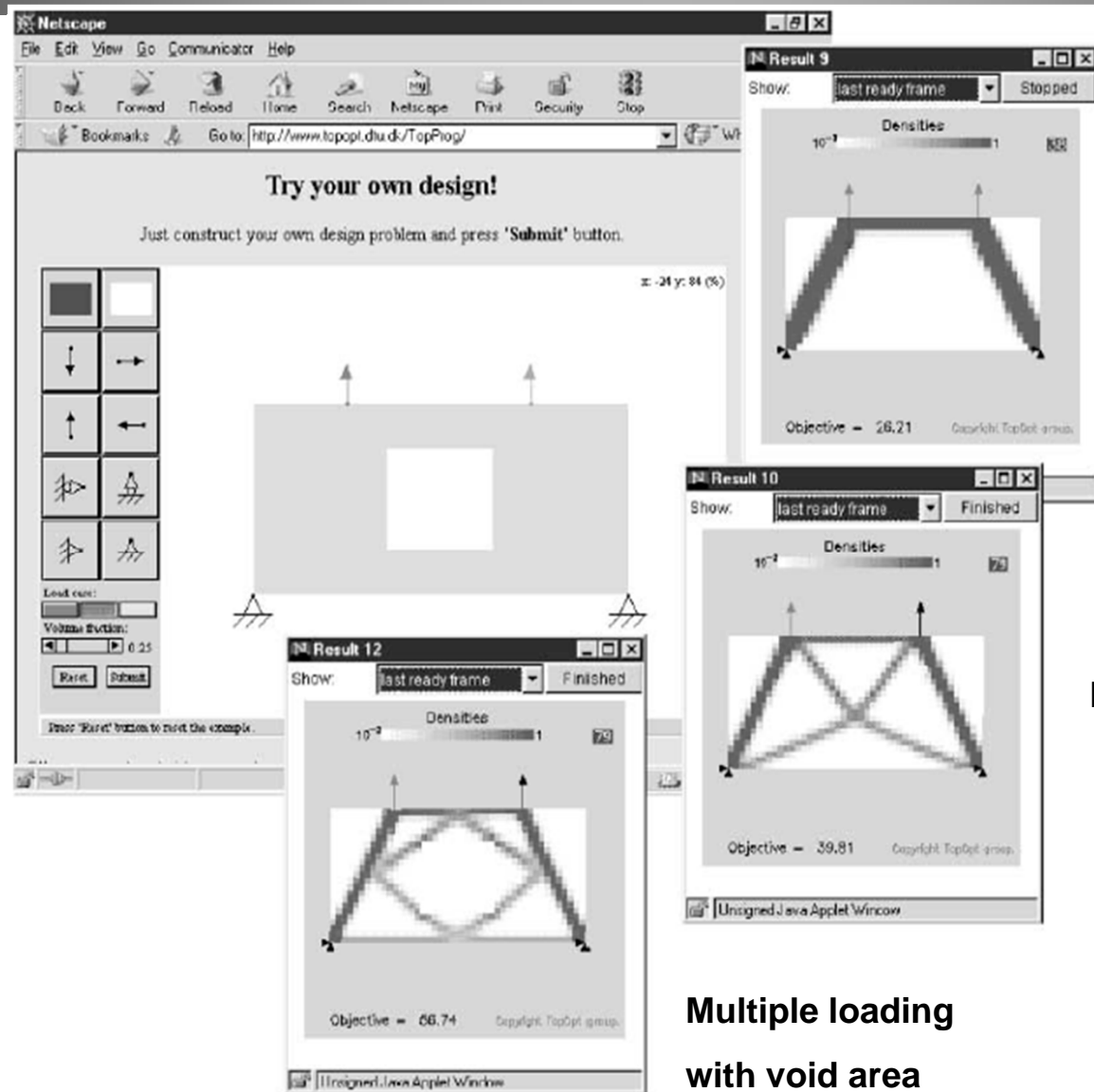


Vehicle Structure



Design Optimization - 12

Educational Design Tool (2)



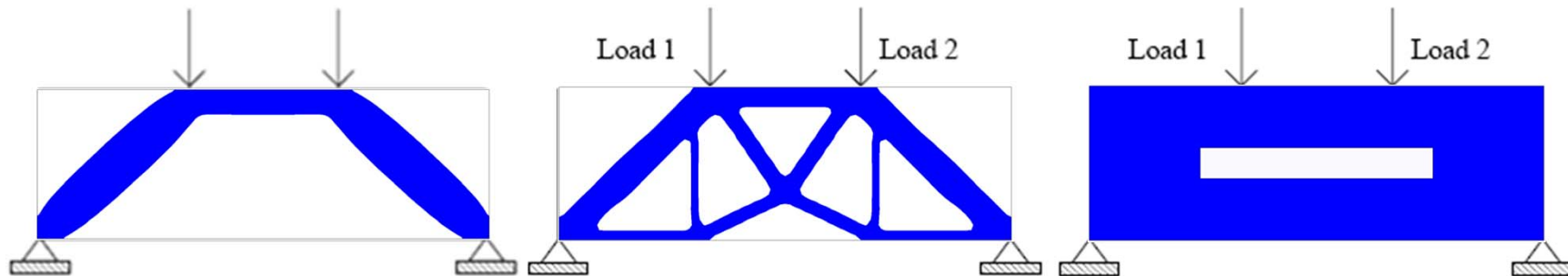
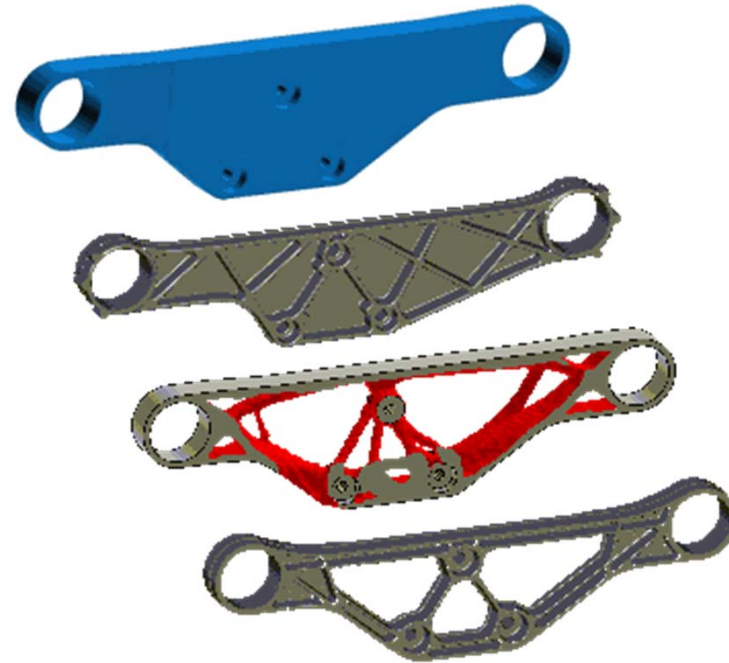
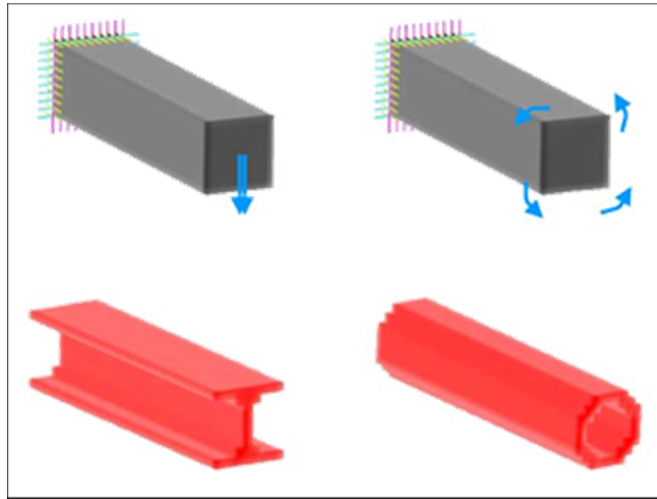
Single loading

Multiple loading

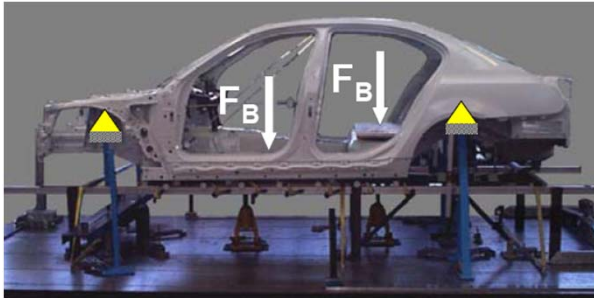
Multiple loading with void area

정적 문제: 예제

고체역학 검증: 하중 경로

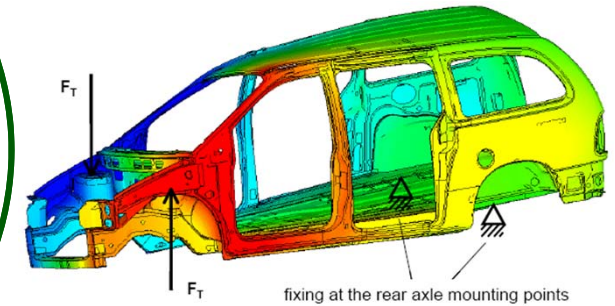
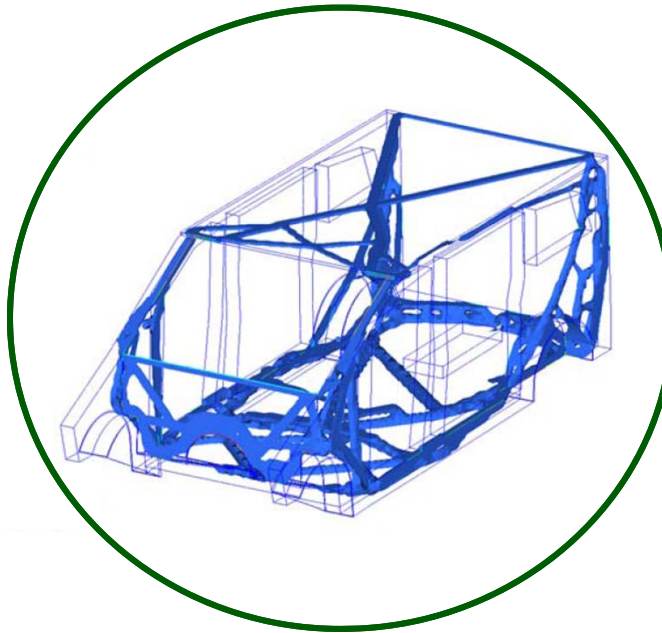
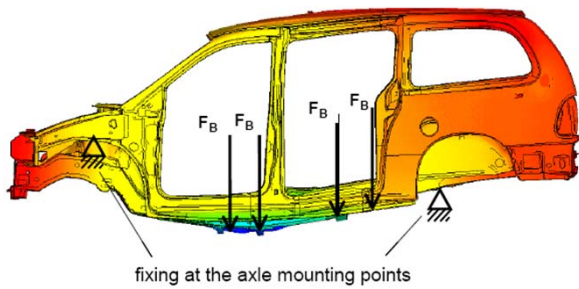


위상최적설계: 개념 설계에 활용

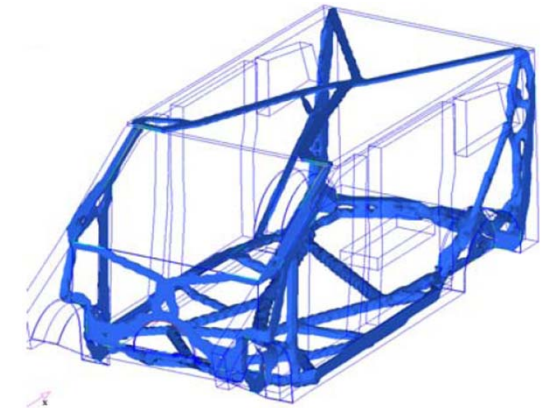
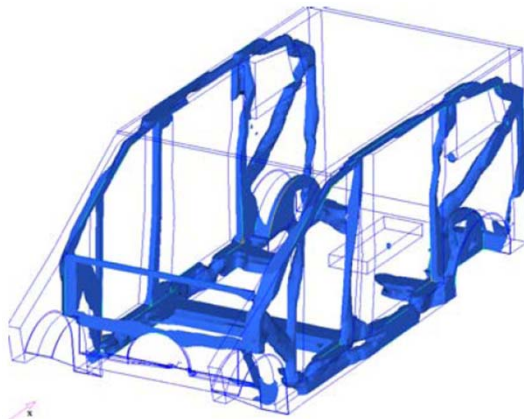


굽힘

비틀림



굽힘 + 비틀림



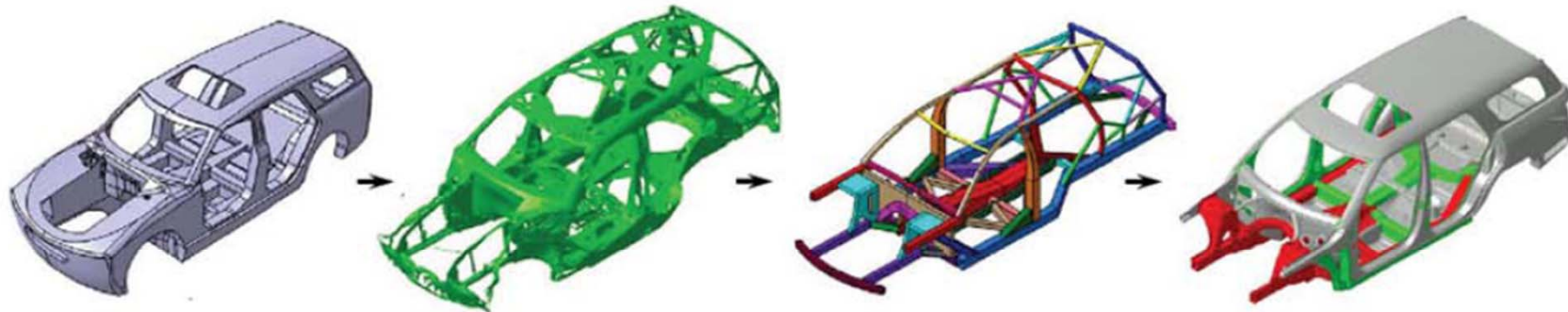
위상최적설계: 차체구조설계 사례



Light Weight Body Structural Optimization Process

2008 GDIS

Topology Optimization used to define Major Load Paths



Packaging Volume

Holistic Drivers

- Safety
- NVH Refinement
- Durability

Topology Results

Spatial load image

Beam Model

87 paths

BIW Design

202 components

Chassis: Ferrari F458 Italia

- 설계 목적

경량화

- 설계 변수 (cascade)

Topology optimization: 밀도

Topometry optimization : 절점 높이

Size optimization : 셸 두께

- 성능 요구조건

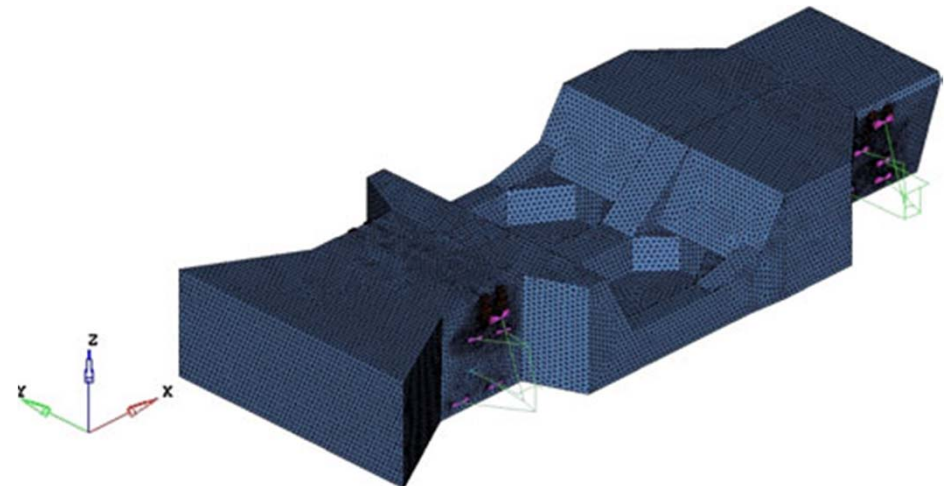
global bending stiffness
global torsional stiffness
Local stiffness of the suspensions, engine and gearbox
Modal response
Crash linearization

Struct Multidisc Optim (2011) 44:45–56
DOI 10.1007/s00158-010-0578-7

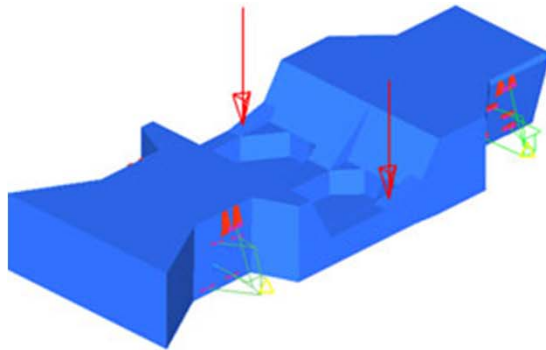
INDUSTRIAL APPLICATION

High performance automotive chassis design: a topology optimization based approach

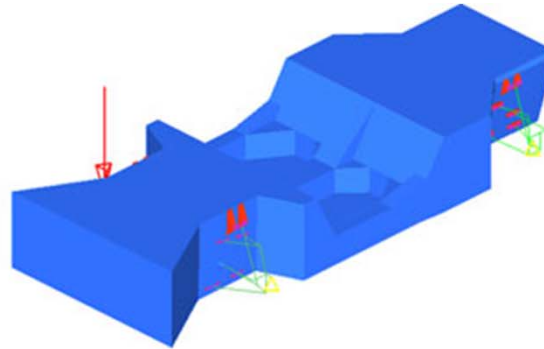
Marco Cavazzuti · Andrea Baldini · Enrico Bertocchi ·
Dario Costi · Enrico Torricelli · Patrizio Moruzzi



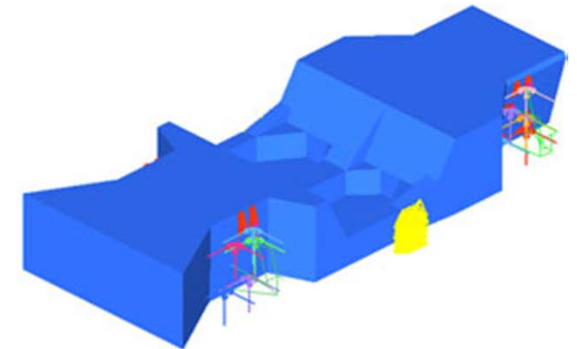
Chassis: 하중조건



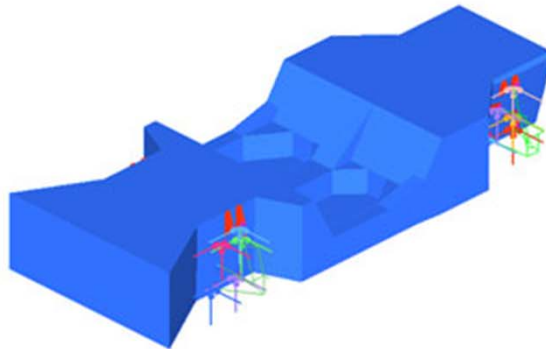
bending stiffness (1 FEA)



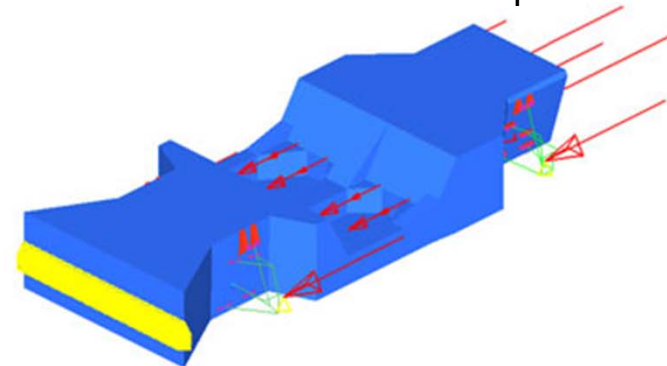
torsional stiffness (1 FEA)



local stiffness with
clamped sills (32 FEA)

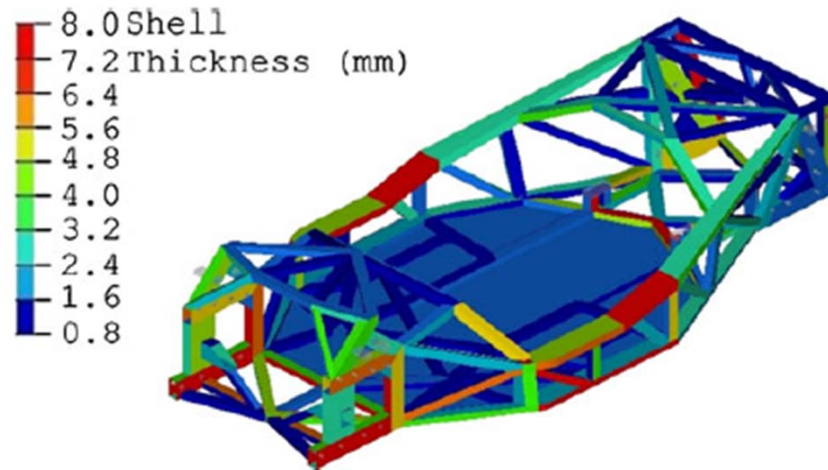
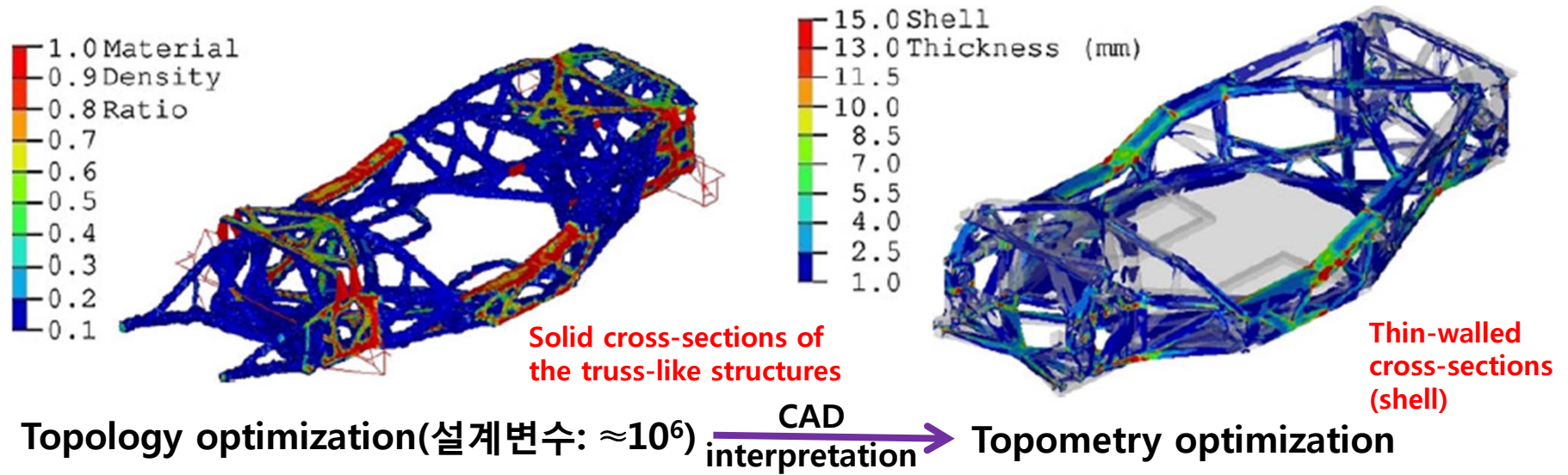


local stiffness with
inertia relief (32 FEA)

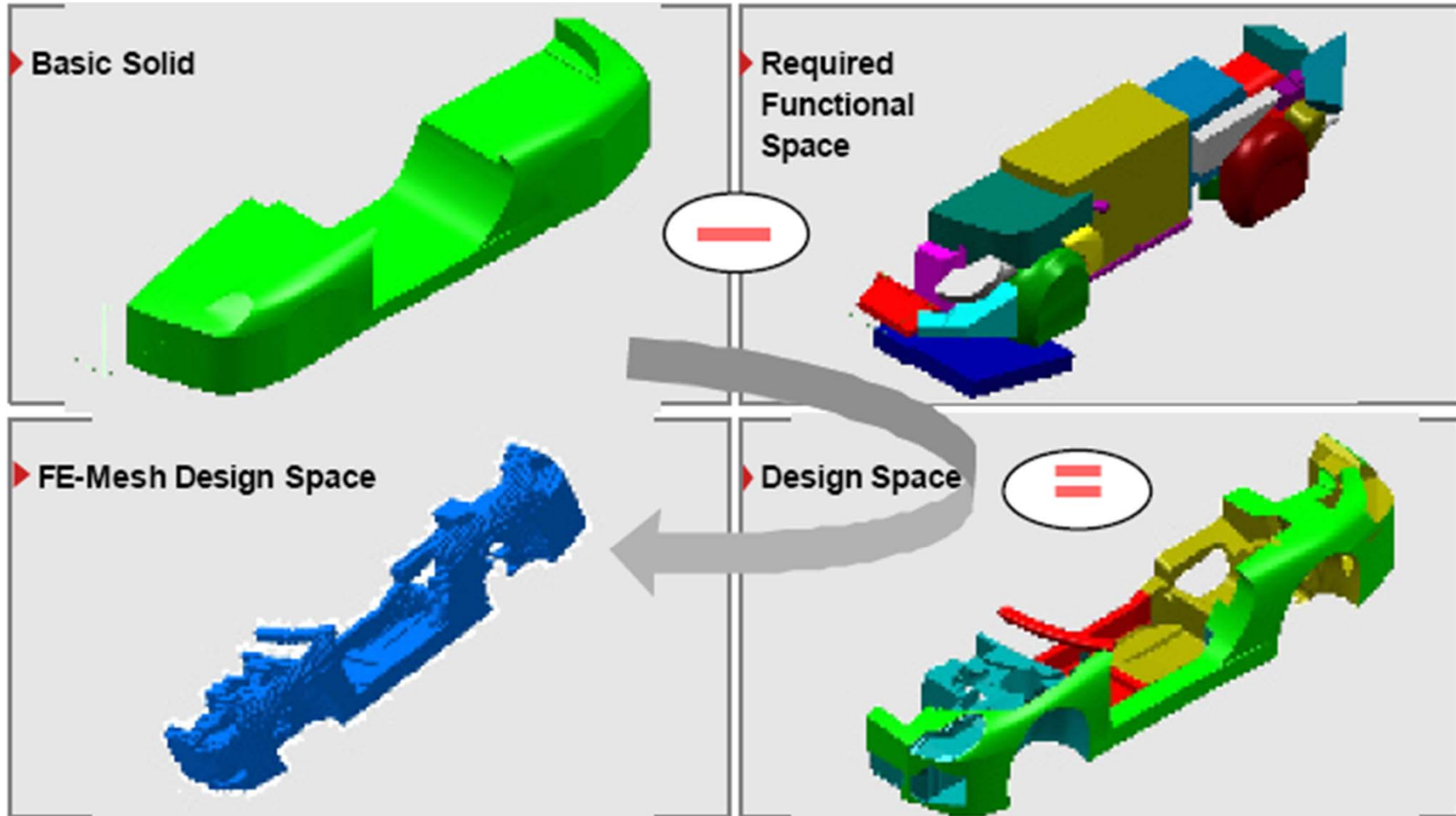


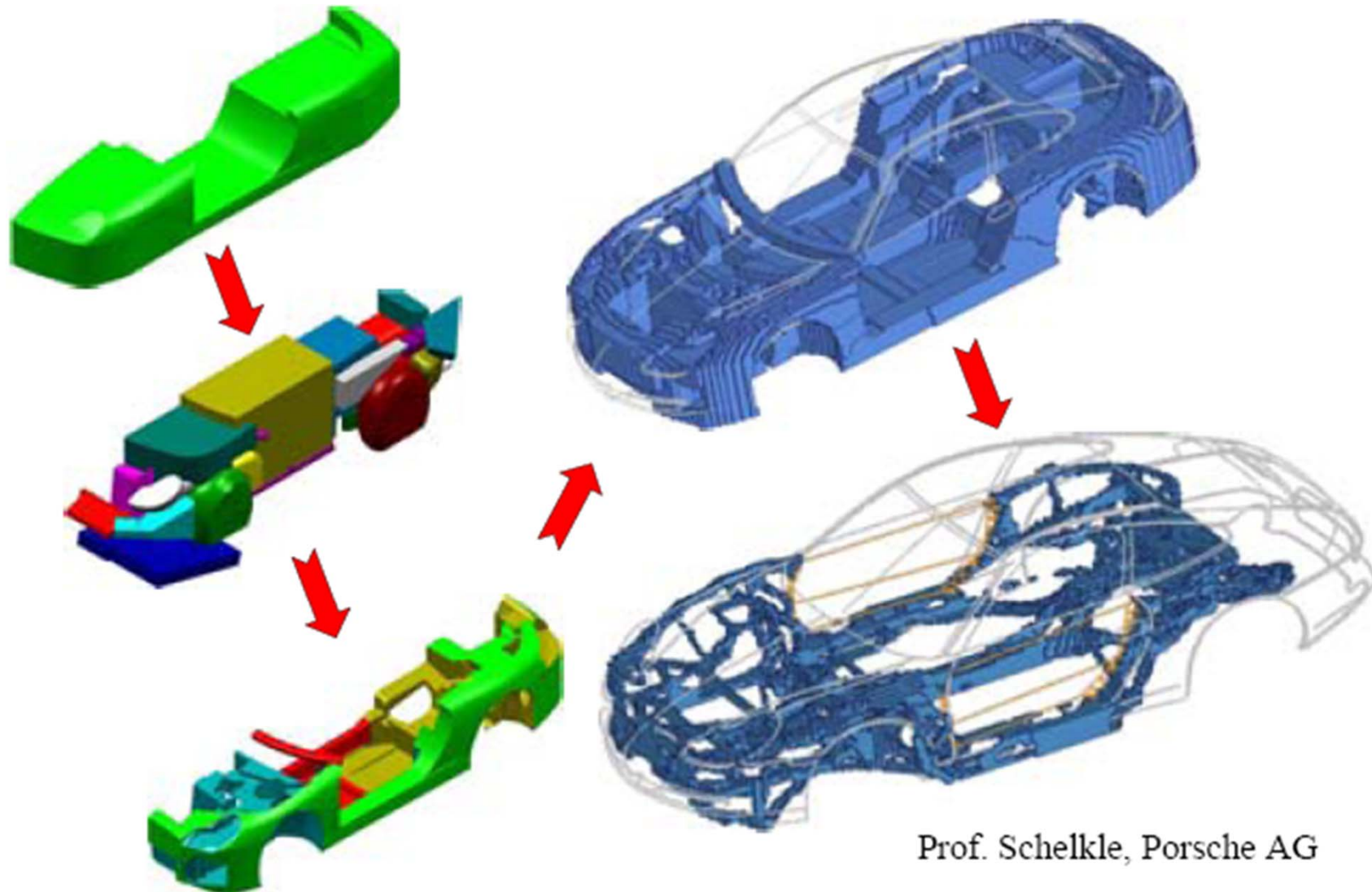
crash linearization (1 FEA)

Chassis: 최적설계

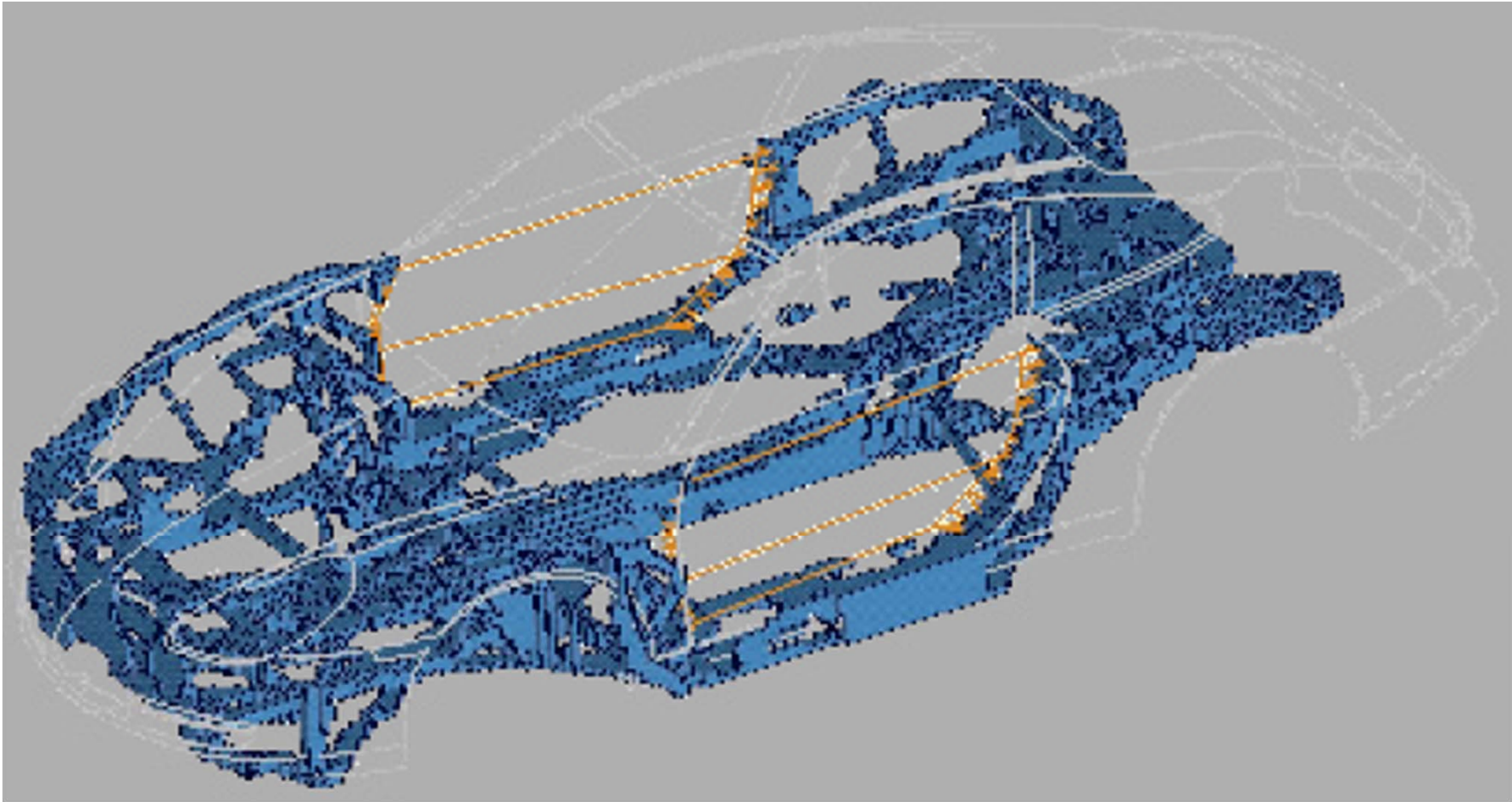


Load Path Analysis Sequence

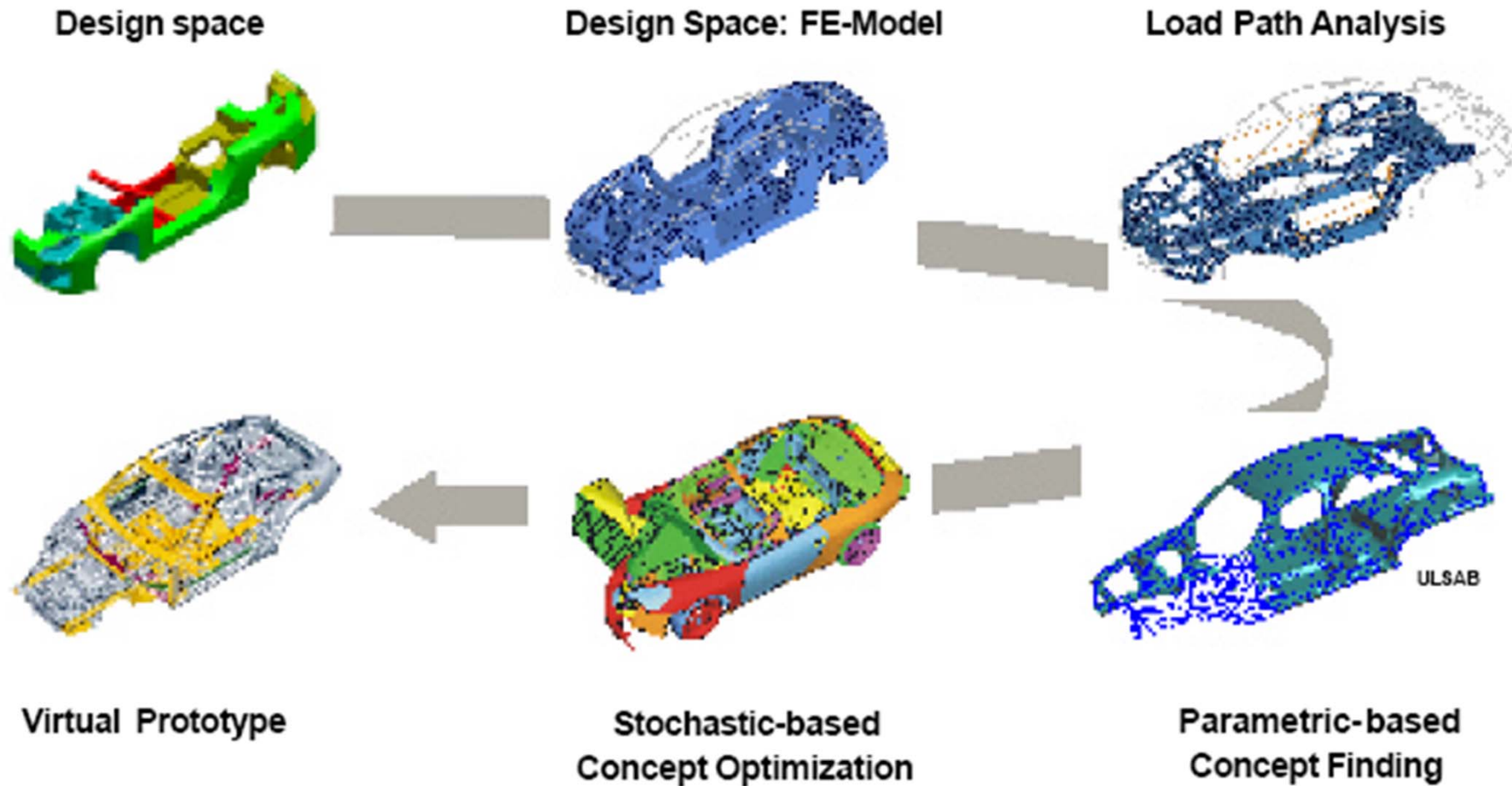




Prof. Schelke, Porsche AG



Concept Stage of Vehicle Development



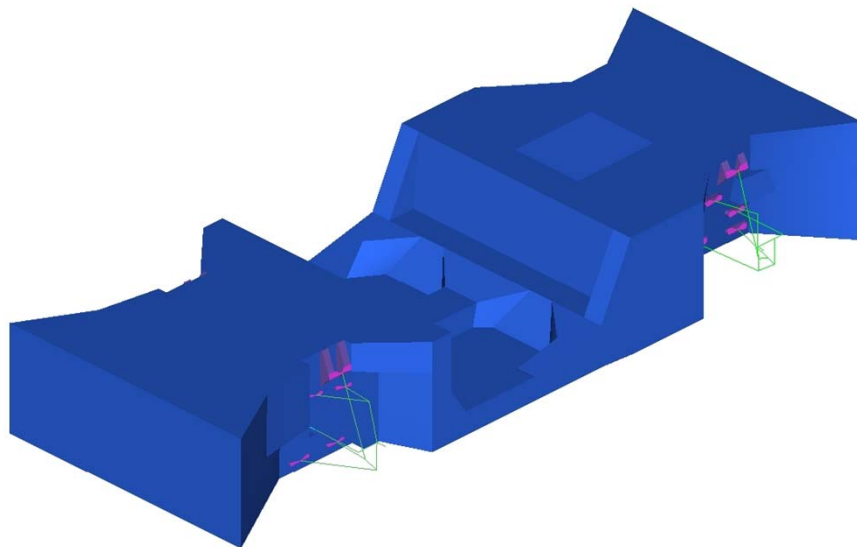
Automotive Chassis

Proceedings of the World Congress on Engineering 2011 Vol III
WCE 2011, July 6 - 8, 2011, London, U.K.

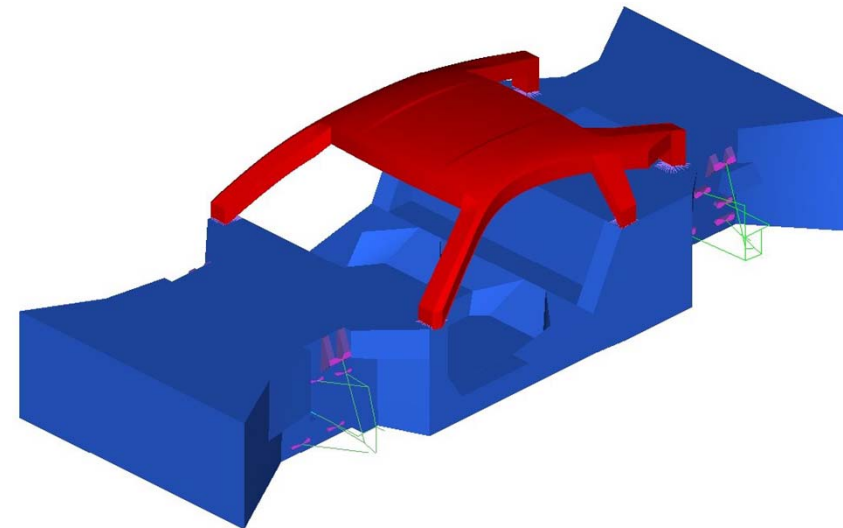
Automotive Chassis Topology Optimization: a Comparison Between Spider and Coupé Designs

Marco Cavazzuti, Dario Costi, Andrea Baldini, Patrizio Moruzzi

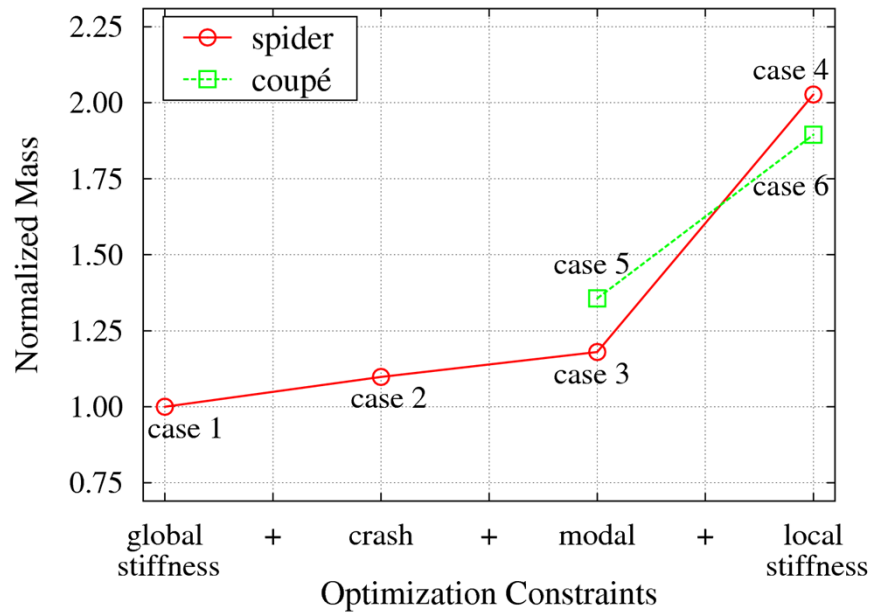
- Comparison Between Spider and Coupé Designs



Vehicle Structure

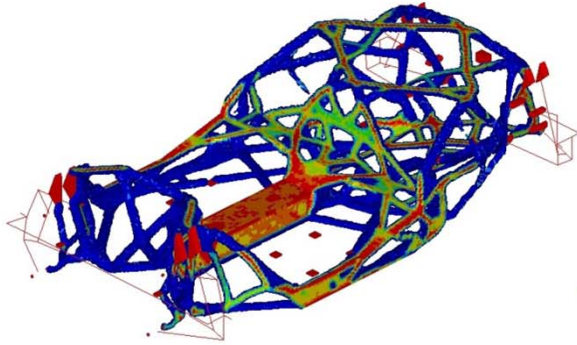


Design Optimization - 24

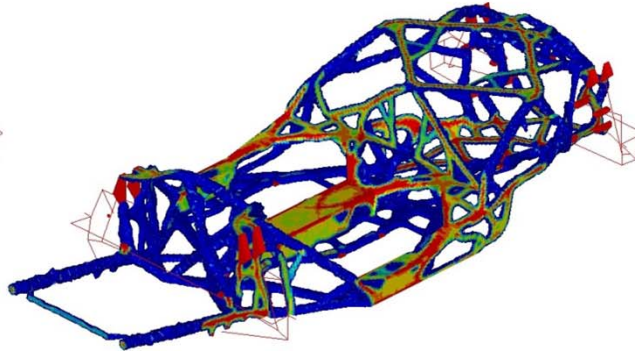


Active Optimization Constraints	Cases					
	Spider				Coupé	
	1	2	3	4	5	6
Global bending stiffness	✓	✗	✓	✓	✓	✓
Global torsion stiffness	✓	✓	✓	✓	✓	✗
Crash seat joints displacement	–	✗	✗	✗	✓	✗
Crash engine joints displacement	–	✓	✓	✗	✓	✓
Crash A-pillar displacement	–	✓	✓	✓	✓	✓
Crash pedal displacement	–	✗	✓	✗	✗	✗
Crash flame shield displacement	–	✓	✓	✗	✗	✗
Crash dashboard joints displacement	–	✗	✗	✗	✗	✓
Crash compliance	–	✓	✓	✓	✓	✓
First natural mode	–	–	✓	✓	✓	✓
Local front wheel stiffness along x	–	–	–	✓	–	✓
Local front wheel stiffness along y	–	–	–	✓	–	✓
Local front wheel stiffness along z	–	–	–	✓	–	✓
Local rear wheel stiffness along x	–	–	–	✓	–	✓
Local rear wheel stiffness along y	–	–	–	✓	–	✓
Local rear wheel stiffness along z	–	–	–	✗	–	✗
Local engine joint stiffness along z	–	–	–	✓	–	✓
Local gearbox joint stiffness along z	–	–	–	✓	–	✗
Total	$\frac{2}{2}$	$\frac{5}{9}$	$\frac{8}{10}$	$\frac{12}{18}$	$\frac{7}{10}$	$\frac{12}{18}$

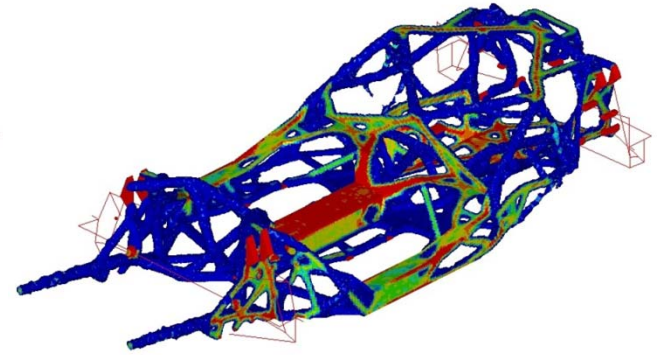
Results (1)



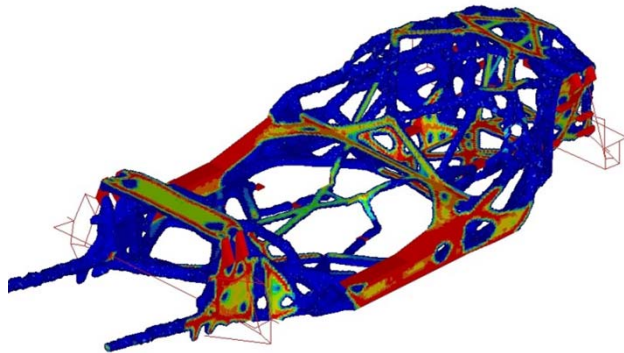
Case 1



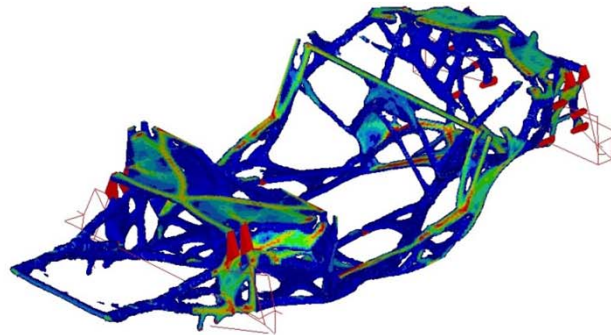
Case 2



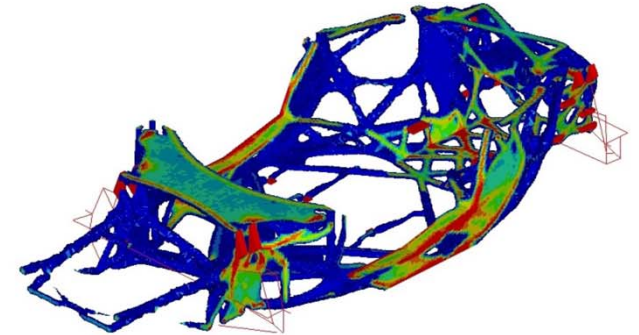
Case 3



Case 4

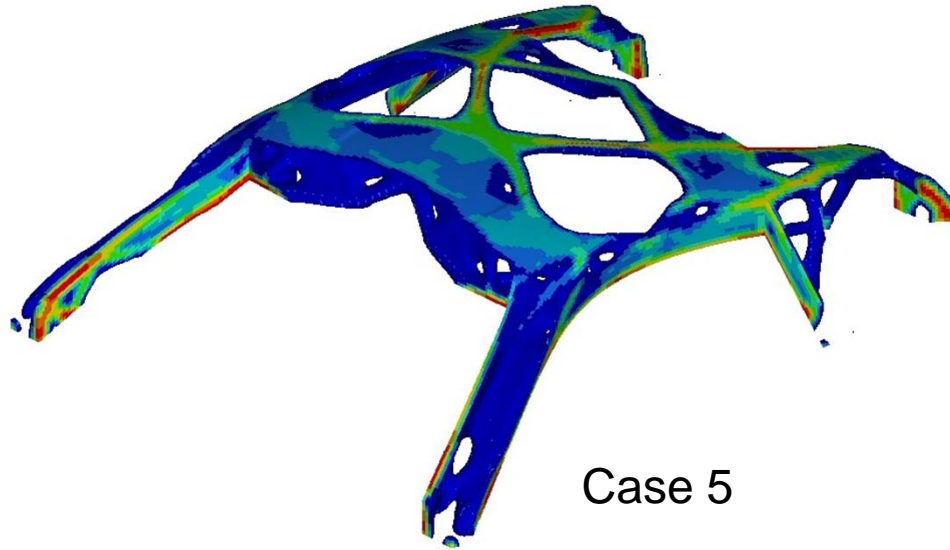


Case 5

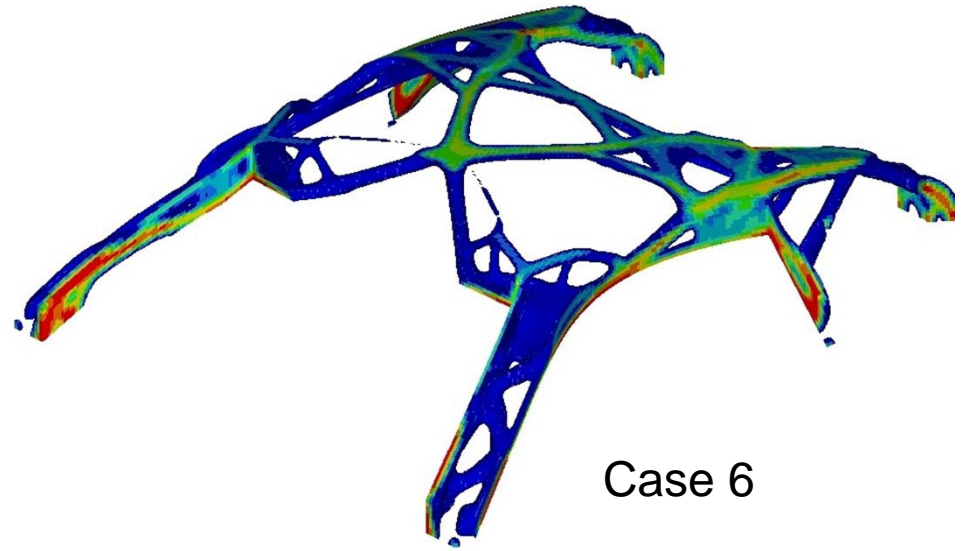


Case 6

Results (2)



Case 5



Case 6

설계프로세스에 적용

FutureSteelVehicle

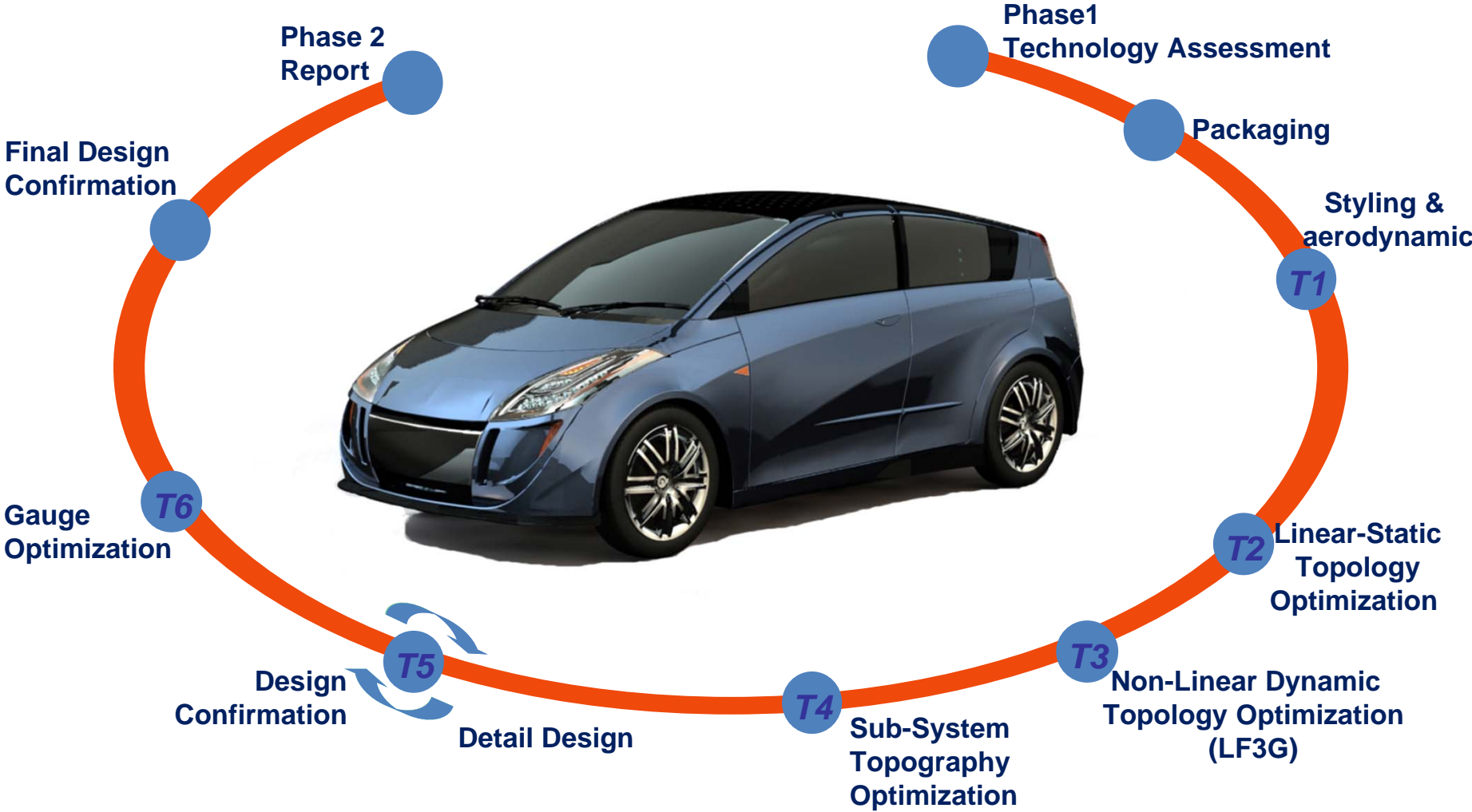


Nature's Way to Mobility

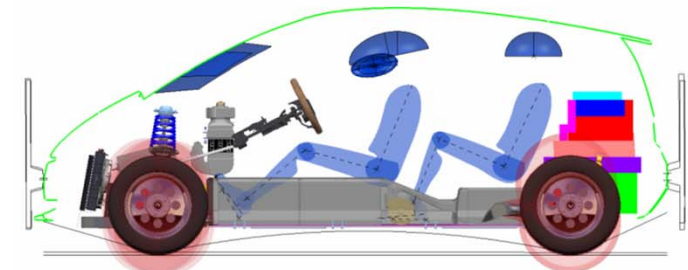
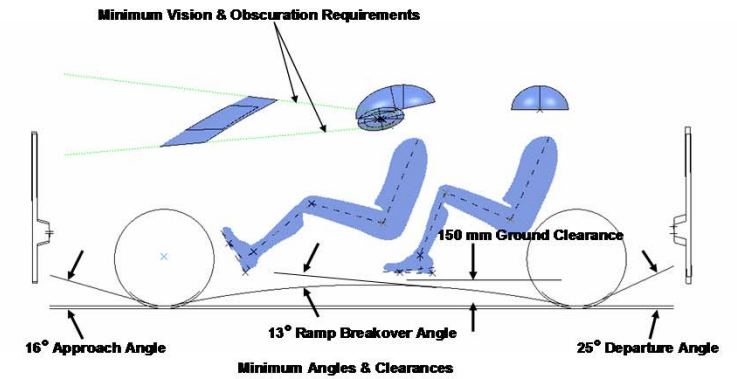
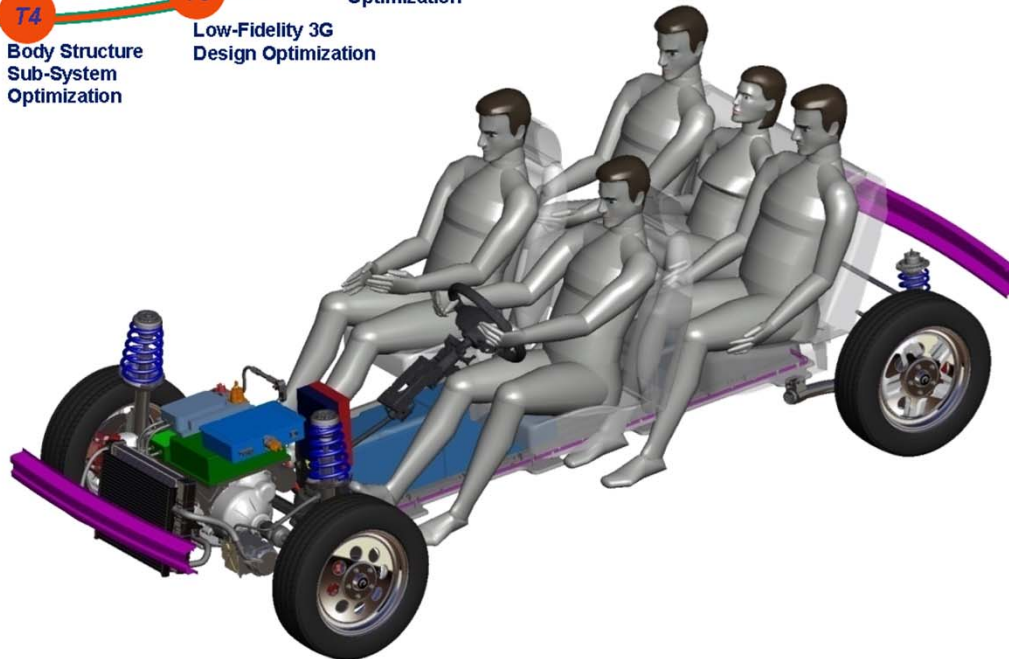
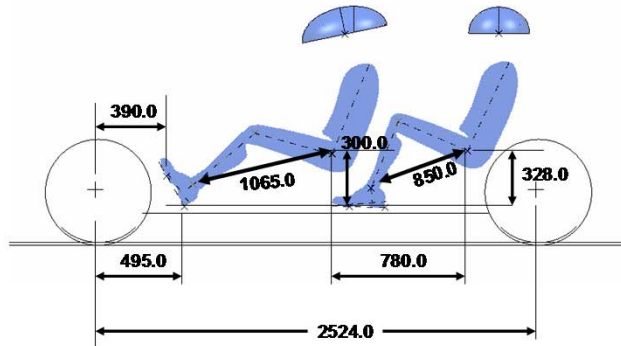
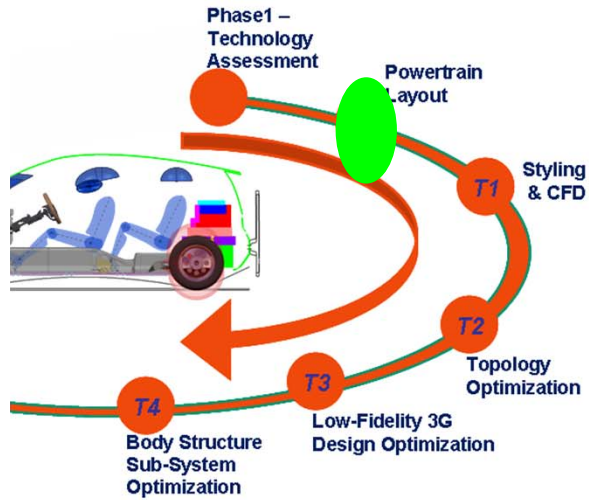
ULSAB-AVC
Advanced Vehicle Concepts



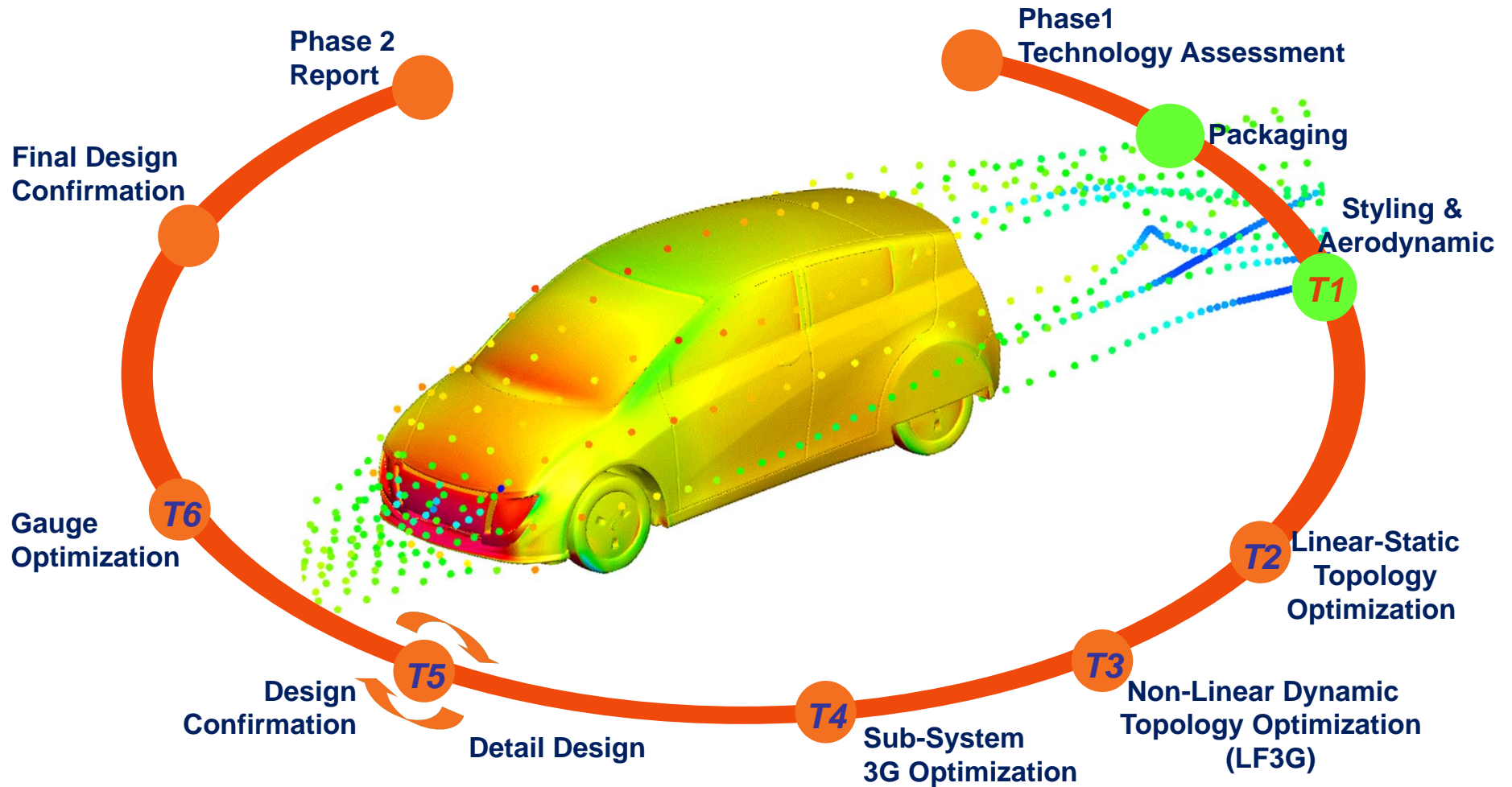
FSV Design Methodology



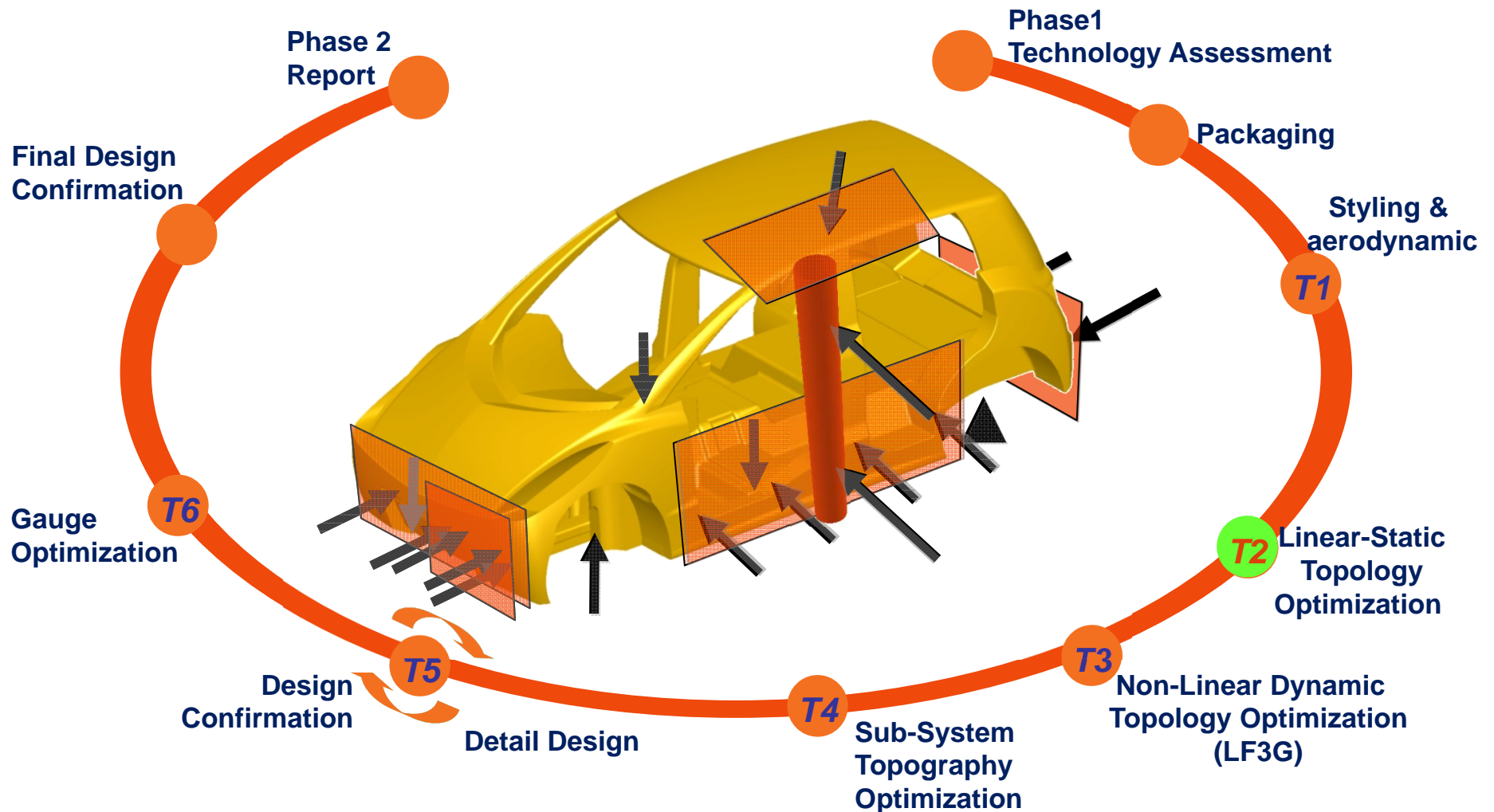
FSV BEV Packaging



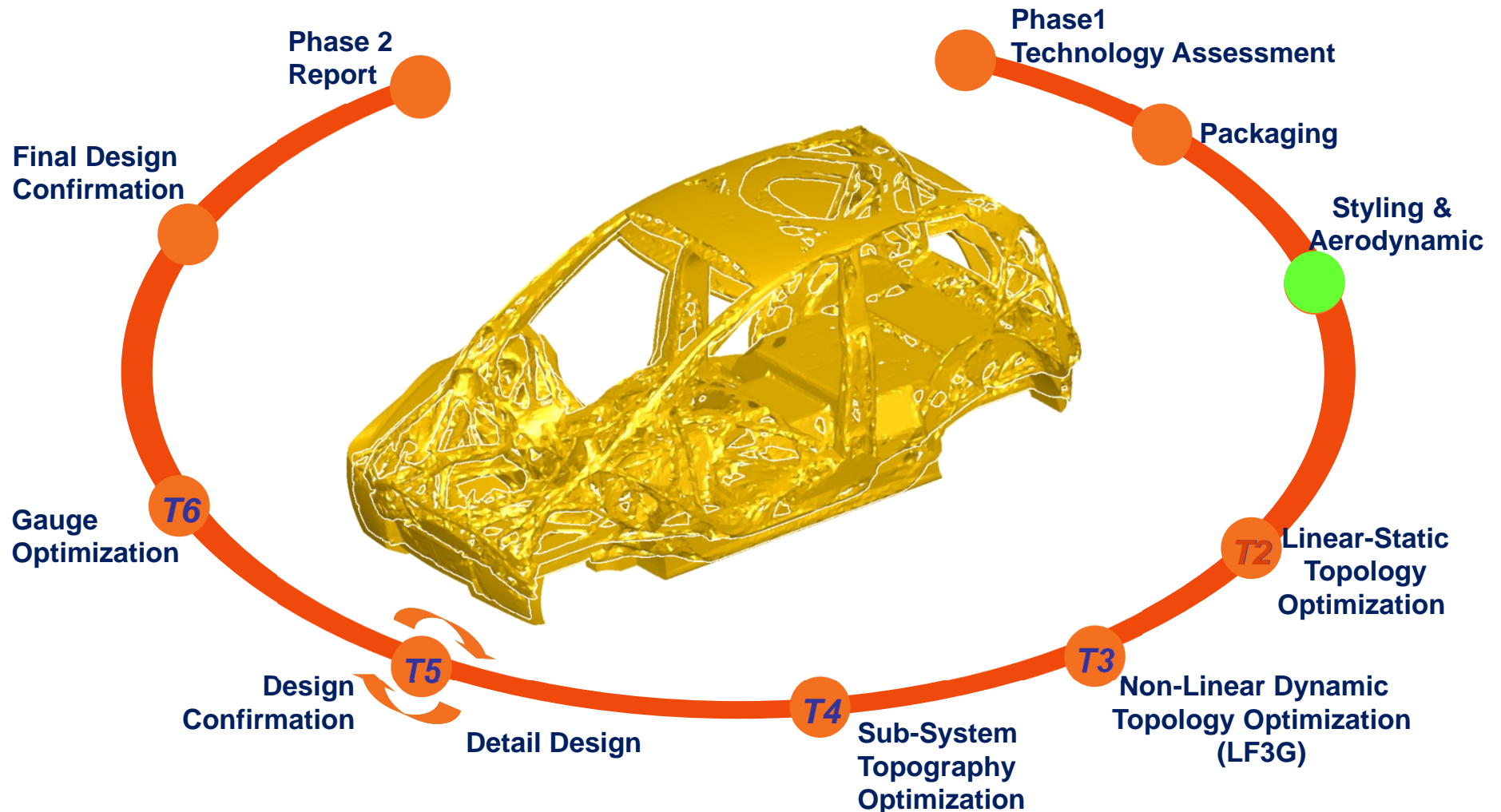
Aerodynamics & Styling



Topology Optimization Load Cases

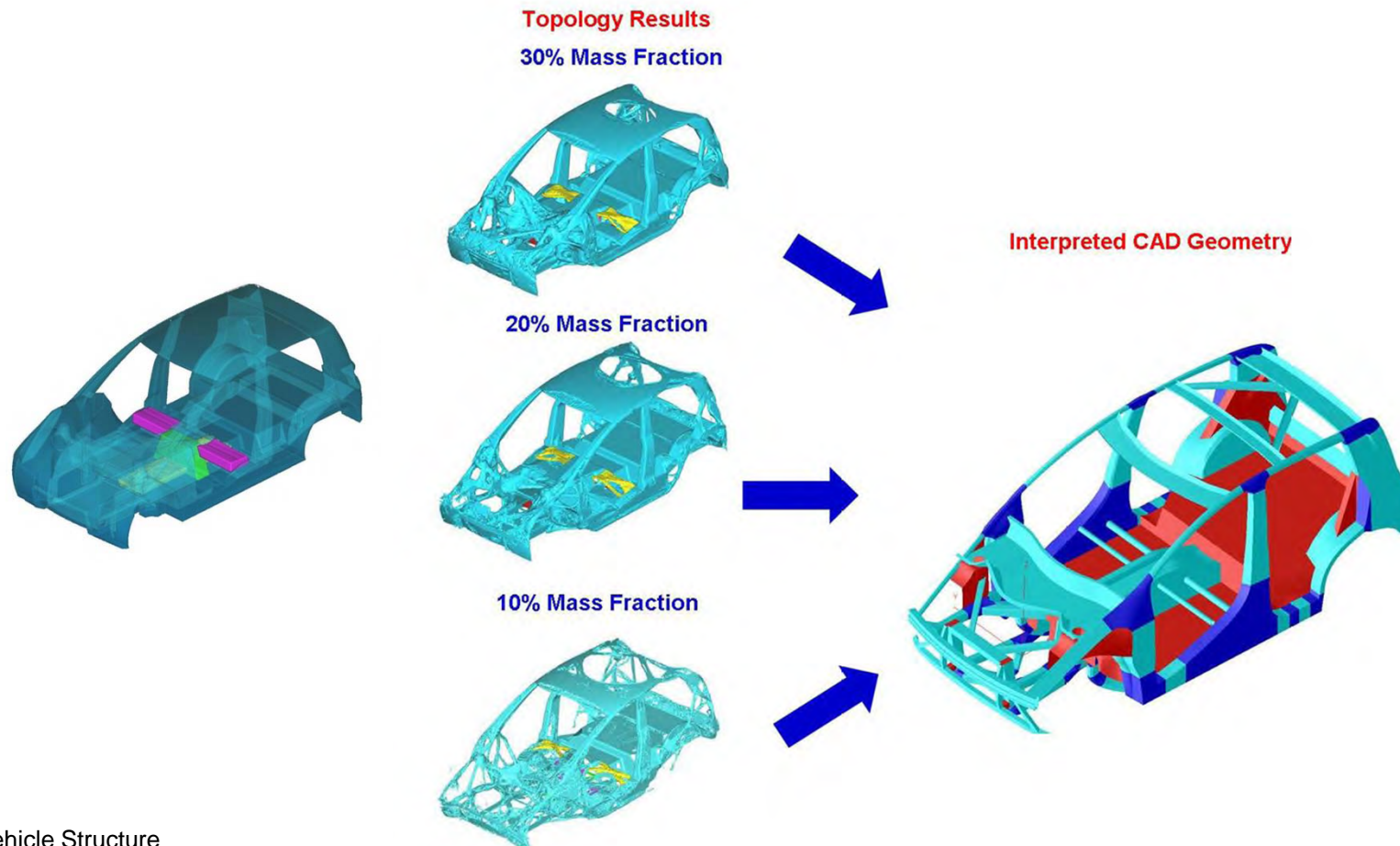


Linear-Static Topology Optimization

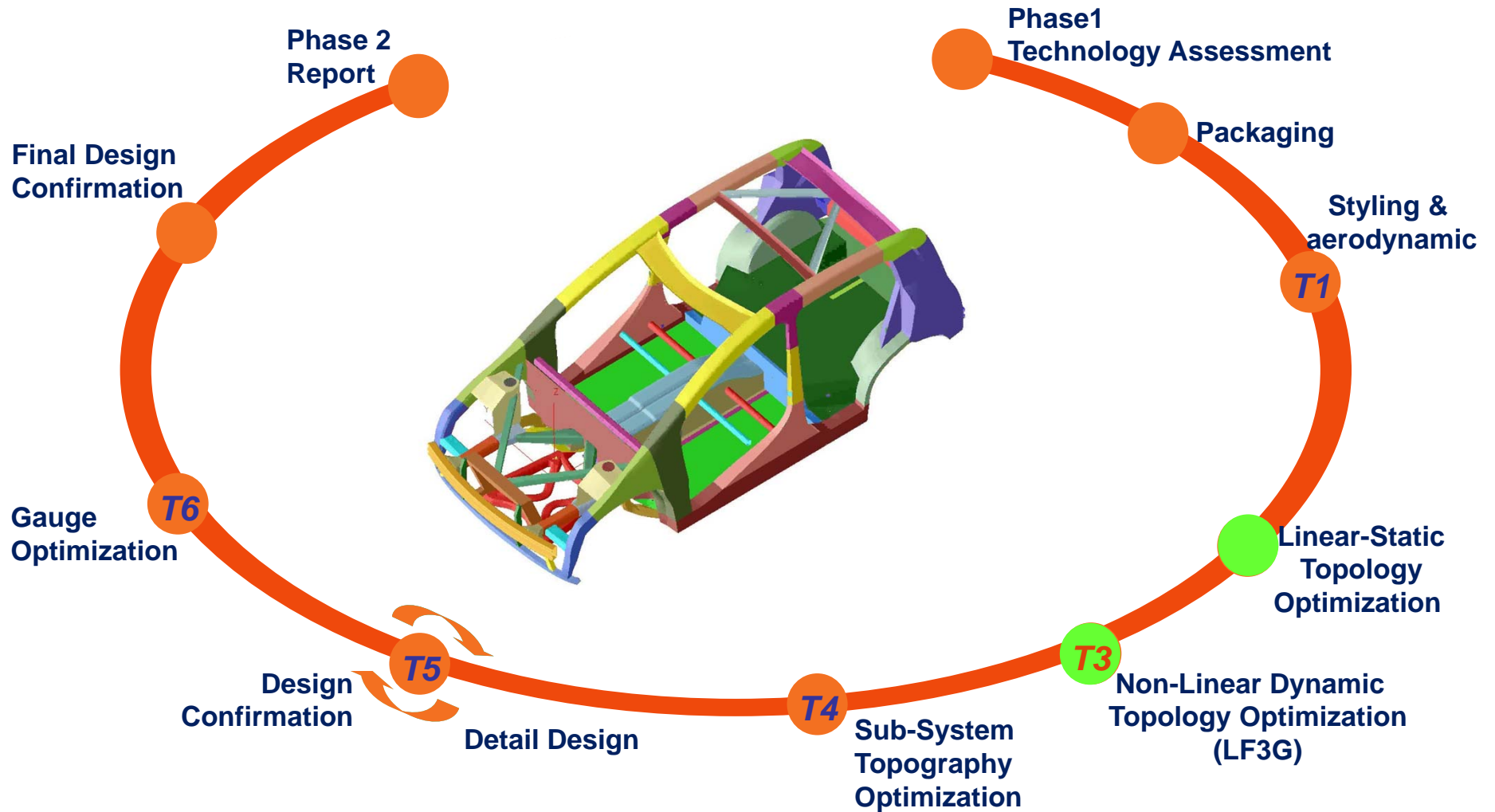


T2: Topology Optimization

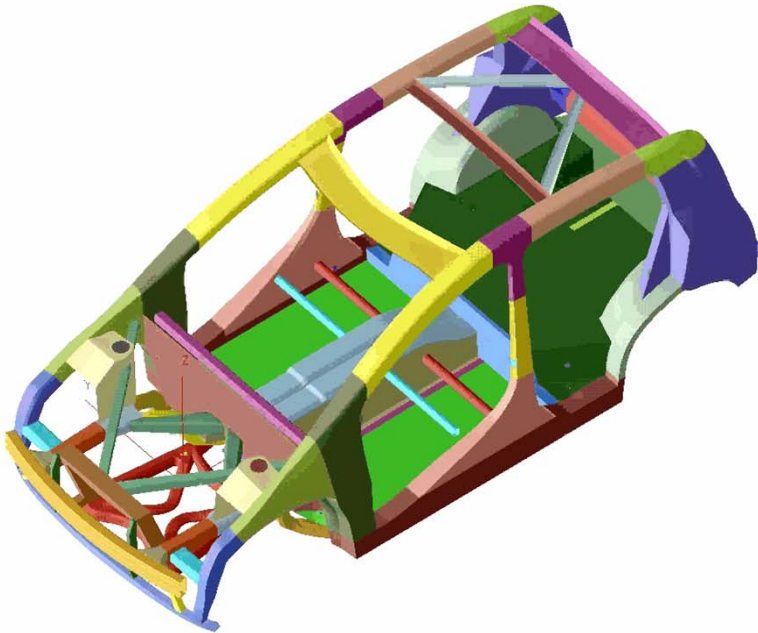
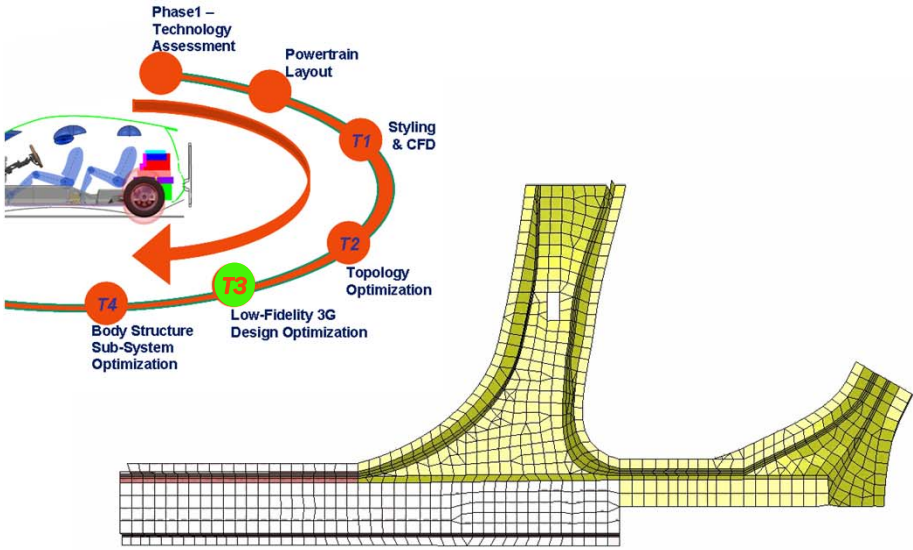
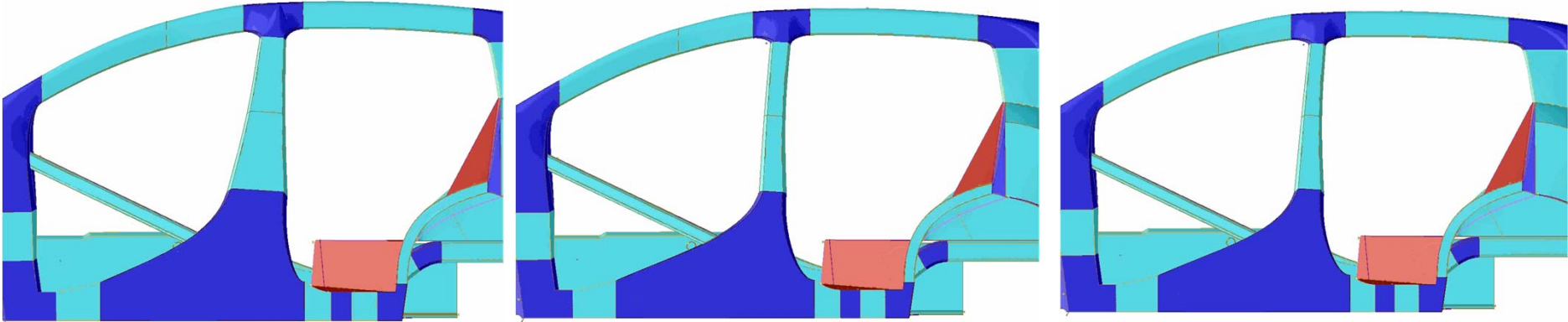
- geometry developed by the topology optimization was manually interpreted into a CAD (Computer Aided Design) model using engineering judgment



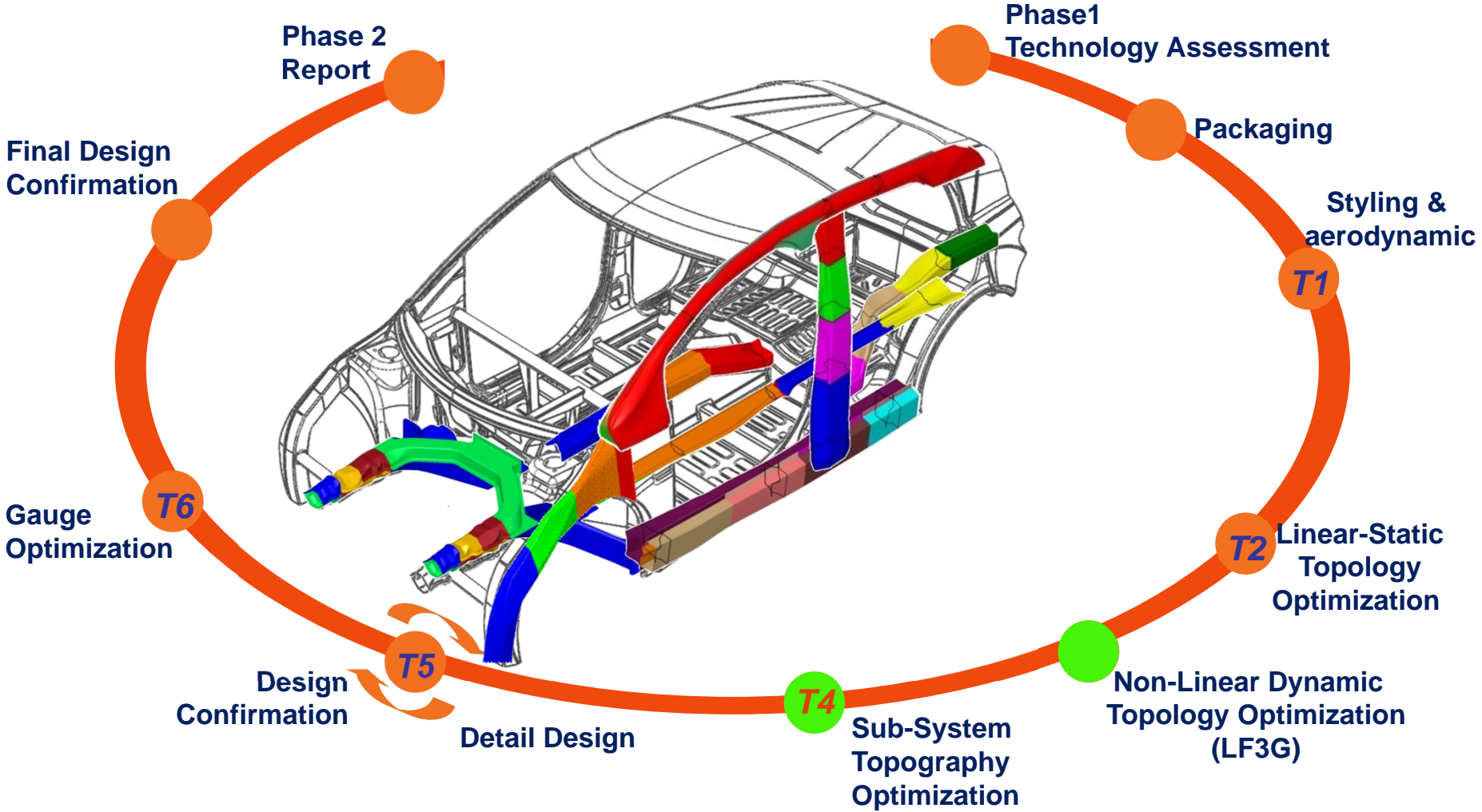
LF3G Load Path and 3G Optimization



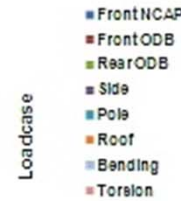
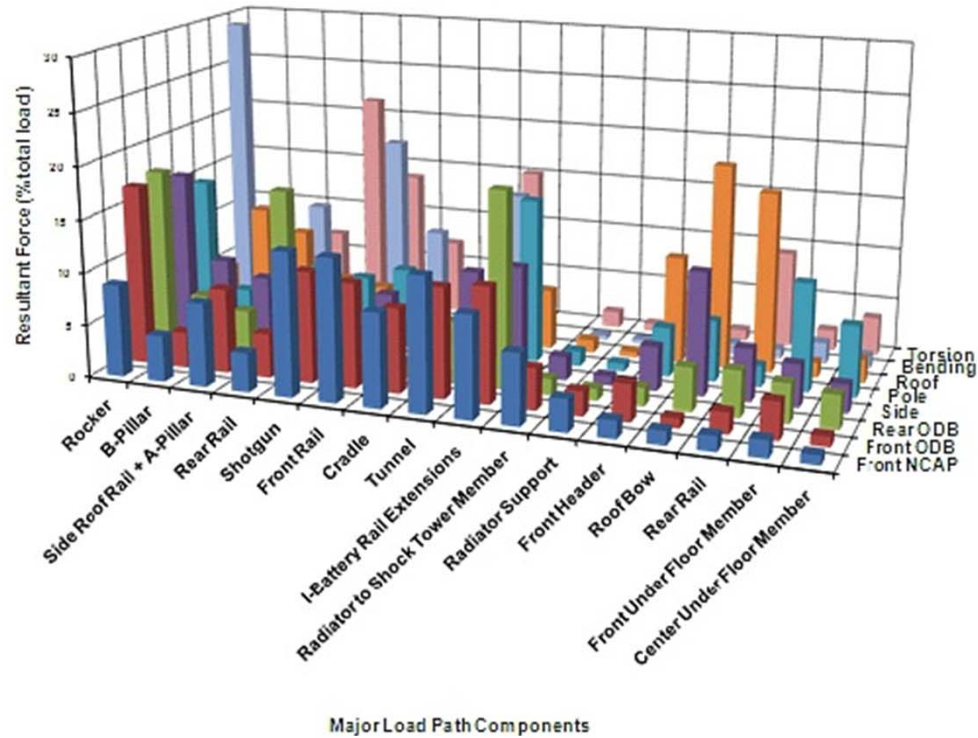
Low Fidelity 3G (Geometry, Gauge & Grade) Optimization



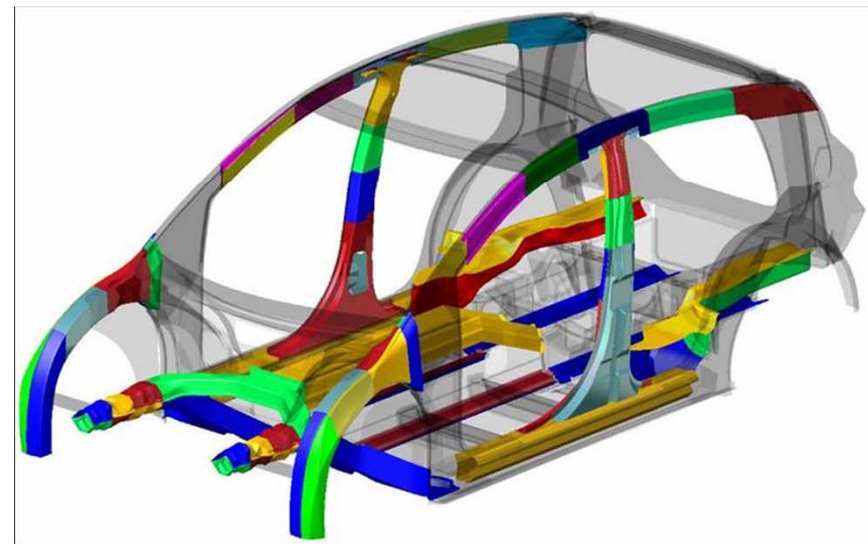
Sub-Systems 3G Optimization



T4 Load Path Mapping

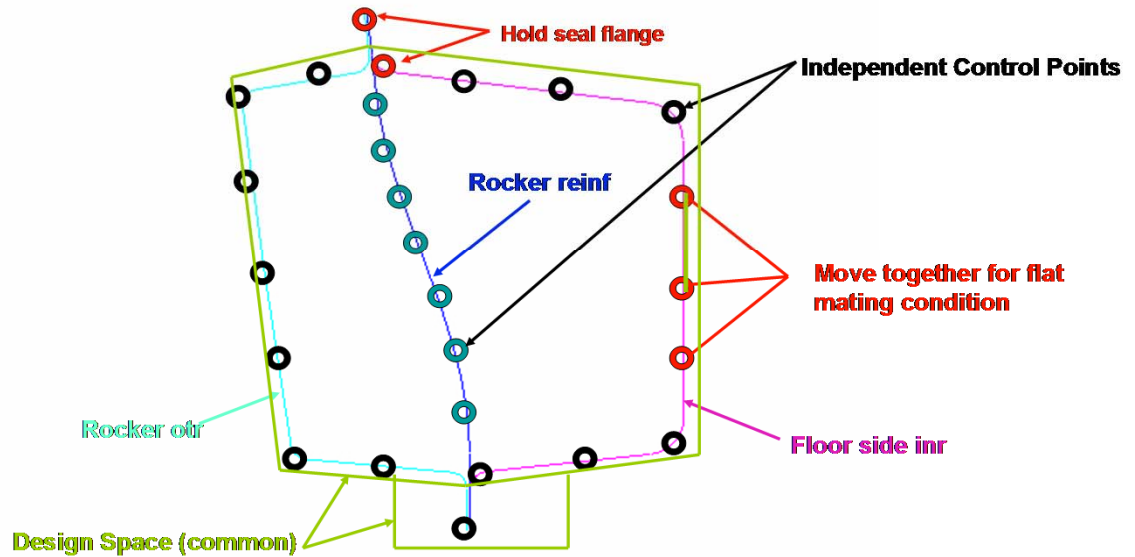
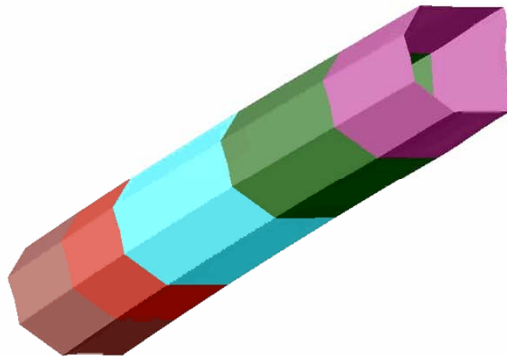
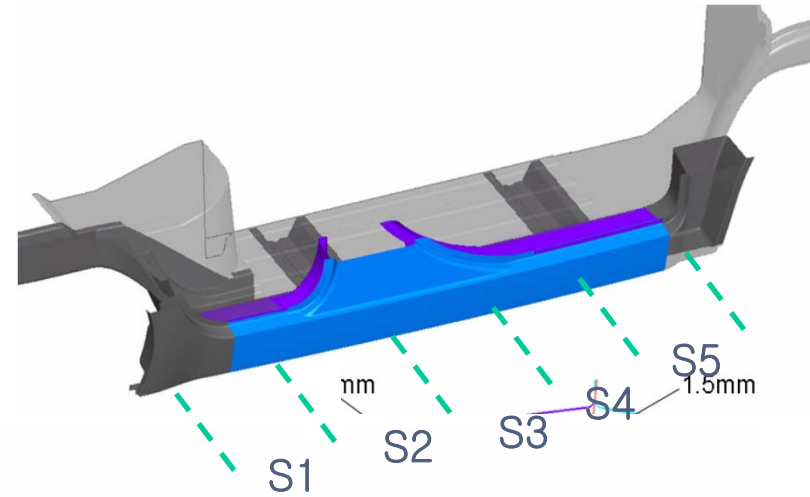
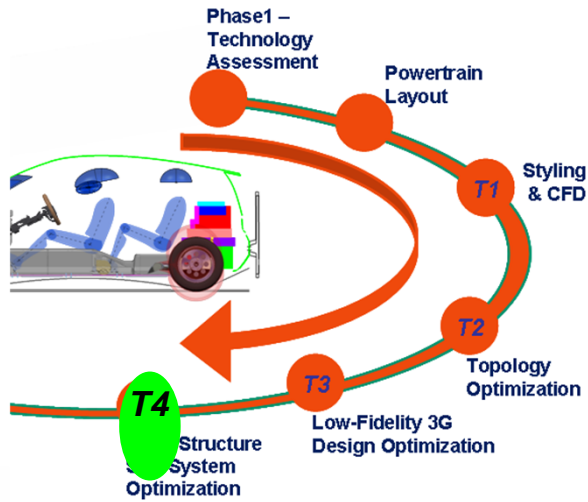


Selected Sub-Systems



- Front Rail
- Shot Gun
- Rocker
- B-Pillar
- Rear Rail
- Roof Rail
- Tunnel Reinforcement

Body Structure – Sub-System 3G Optimization



정리: 위상최적설계

- 구조물 설계에 있어서 CAE 주도 설계: 위상최적설계가 최적격이자 필수
- 초기설계 없이도 구조물 최적설계 가능
 - 개념설계단계에서 효과적
 - 선행(Up-Front) CAE에 적합
 - 구조물 경량화에 큰 공헌: 혁신설계
- 설계자에게 사용 가능한 도구로 발전하기 위한 주안점

