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Topology and sizing optimisation of integral bus chassis with the use of a cooperative coevolutionary genetic algorithm with independent ground structures

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1. Abstract
It is an attractive field to apply structural optimisation on bus body to enhance its performances. Since chassis is the most complex part of the bus body and bears most of loads, this paper focuses on the simultaneous topology and sizing optimisation of an integral bus chassis by treating it as a discrete variable optimisation problem. The objective is to reduce the mass. The torsional stiffness, the foundational frequency and the max Von Mises stress under full-loaded bending case are constrained. Meanwhile, some essential functional and manufacturing requirements are considered. Firstly, the finite element analysis models of the original bus were created and validated by experiments. Then, a special architecture of cooperative coevolutionary genetic algorithm with independent ground structures (CCGA-IGS) is proposed to improve the flexibility of the solution method and decrease the complexity of the optimisation problem: two different ground structures are defined for topology optimisation and sizing optimisation, and then the topological variables and sizing variables are divided into two subpopulations which evolve in two different GA systems but interact with each other in each iteration. Moreover, a strategy is presented to automatically reload the uniformly distributed loads when the topology of the chassis is changed. The weight of the optimal design is decreased as much as 246.45 kg with all the constraints satisfied.
2. Keywords: integral bus chassis; topology optimisation; sizing optimisation; cooperative coevolutionary genetic algorithm; independent ground structures

3. Introduction
Significant progress has been made in theoretical research on structural optimisation of discrete structures, in which application of the theory mostly focuses on ideal simple structures [1, 2]. Theoretical research shows that performances of discrete structures can be improved remarkably with the use of structural optimisation. Recently, much attention has been paid to the application of structural optimisation on practical engineering products, but practical research is still much slower than theoretical research [3]. Typically, structural optimisation consists of topology optimisation, sizing optimisation and shape optimisation, among which sizing optimisation is the most widely employed technique in optimisation of bus body frames. Gauchia, et al. [4] conducted sizing optimisation on a real bus structure for lightweight without spoiling vehicle safety. Su, et al. [2] performed the multi-objective sizing optimisation on an integrated bus body frame to minimize the weight and maximize the torsional stiffness with the constraints of strength and rollover safety.

This paper concentrates on simultaneous topology and sizing optimisation of an integral bus chassis. It is a complex problem to solve. The challenges of solving the problem come from several reasons. First, large number of discrete variables are involved which would deteriorate the performance of the optimisation algorithm [5]. Second, design constraints are diverse including performance constraints, manufacturing constraints, functional constraints and so on. Third, since a bus undergoes various loadings during lifetime, multiple conditions need to be handled, such as linear static analysis, eigenvalue extraction, etc.

Decomposing a complex problem into smaller sub-problems is an effective way to solve problem with large number of variables [6]. A cooperative coevolutionary genetic algorithm (CCGA) proposed by Potter and De Jong [7] is introduced in this paper. In CCGA, variables are assigned into subpopulations that evolve concurrently. Meanwhile, individuals in different subpopulations collaborate with one another for evaluations in each iteration. Cooperative coevolutionary evolutionary algorithms (CCEAs) have achieved successful application in many fields [8, 9], but there is no one versatile architecture suitable for all problems so far. This paper aims to propose a CCGA architecture for simultaneous topology and sizing optimisation of bus body frame chassis.

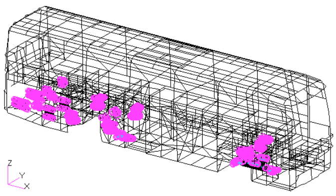
Due to the stochastic nature of GA, structures that cannot be easily manufactured or cannot satisfy functional requirements are easily generated in structural optimisation. Therefore, it is quite necessary to include manufacturing and functional constraints. However, those constraints are usually difficult to be expressed in rigorous mathematical equations. In order to handle those constraints, actions are taken before the optimisation by appropriately defining the design spaces and grouping variables. In order to define design spaces and constraints more flexibly for topology and sizing optimisation, a strategy called independent ground structures (IGS) is presented, where different ground structures are constructed for topology optimisation and sizing optimisation independently. IGS strategy is integrated into the CCGA architecture, and a method named CCGA-IGS is presented, which was implemented on the bus chassis frame.

4. Original Finite Element Model and Validation

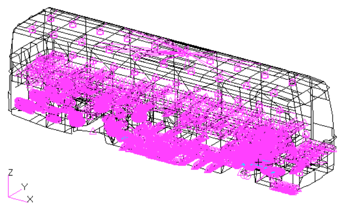
The integral bus used in this paper is a 12-meter-long intercity bus with luggage compartments and toilet, and has a maximum 47-passenger capacity. The performances of the bus are implicit functions of design variables, and finite element analysis method is adopted.

4.1. Original Finite Element Models

The FE model of the original bus body frame is created with beam elements as shown in Figure 1(a), which is used for modal and torsional stiffness analyses. For strength analysis, the FE models of the suspension system, the wheels and full loads are created and assembled with the FE model of the bus body frame, as shown in Figure 1(b).



(a) The FE model of the bus body frame



(b) The FE model for strength analysis

Figure 1: The FE models

Because free vibration of the bus body frame is concerned in this paper, the free-free boundary is used for modal analysis. In the analysis of the torsional stiffness, the boundary constraints are defined as follows: the nodes in the centers of front-right and front-left air spring supports are forced to move 5 mm in opposite z-direction while the rear axle is fixed. The result of finite element analysis provides the reaction forces of the nodes with enforced displacement, and then the torsional stiffness is obtained according to Eq. (1)

$$K_{\psi} = \frac{FL}{\frac{180}{\pi}\left(\frac{2d}{L}\right)} = \frac{\pi F L^2}{360d} \tag{1}$$

Where K_{Ψ} is the torsional stiffness of the bus body frame, F is the reaction force, L is the distance between the nodes with enforced displacement, and d is the enforced displacement. Here, L=1266 mm and d=5 mm.
In the strength analysis, the max Von Mises stress under full-loaded case is taken into consideration. The boundary condition for strength analysis is that all rigid body displacements of the bus are removed via fixing the translational degrees of freedom of the nodes of the wheels which are connected with the ground.
The material of the bus body frame is Q345C whose Elasticity modulus is 206 GPA, Poisson ratio is 0.3, density is 7.86×10^3 kg· m^{-3} and Yield limit is 510 MPA.

4.2. Validation

Modal test and static bending test were carried out to validate the accuracy of the FE models. In the modal test, the bus body frame was supported by inner tubes whose natural frequency is less than 2 Hz. The comparison of the first seven natural frequencies between the test and the simulation is listed in Table 1, which shows that the difference between the test and the simulation is small. The maximum difference occurs at the second natural frequency, with a difference of 9.60%.

Table 1: Comparison of the natural frequencies between the test and the simulation

Mode No.	Test / Hz	Simulation / Hz	error	Mode No.	Test / Hz	Simulation / Hz	error
1-first torsion	8.38	7.73	-7.76%	2	9.25	10.14	9.60%
3	11.88	12.37	4.16%	4	14.25	13.64	-4.31%
5	15.75	15.27	-3.07%	6	17.00	16.81	-1.11%
7-first bend	17.94	17.74	-1.08%				

In static bending experiment, the front and rear axles were supported and sand pails that totally weigh 1320kg and 840 kg were evenly put on the passenger floors and compartment floors respectively. It should be noted that the

loading case in the test was different from the case used in the optimisation mentioned in Section 4.1. The Von Mises stress of four points on the bus body frame were obtained. For comparison, the loading case used in the test is also loaded on the FE model. The comparison is offered in Table 2. The maximum difference between the test and the simulation is 11.75% at the second point.
In conclusion, the FE models created above is adequate for the optimisation.

Table 2: Comparison of the stress between the test and the simulation

Test Point	1#	2#	3#	4#
Test / MPA	45.24	27.83	30.49	31.31
Simulation / MPA	44.85	31.1	27.9	32.45
error	-0.86%	11.75%	-8.49%	3.65%

5. CCGA-IGS architecture

5.1. Independent ground structures (IGS)

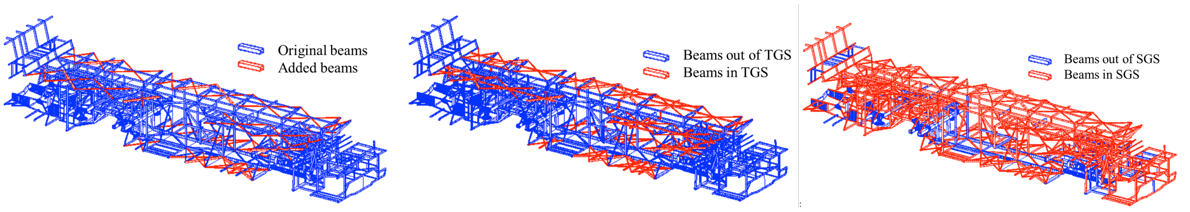
The chassis frame is a very complex structure on which multiple loads are applied, including the power system, the transmission system, the steering system, and the passenger seats etc. As an engineering product, the layout of the chassis frame is required to satisfy the predefined functions. For example, beams should be arranged suitably for the installation of the aforementioned loads, and specific spaces should be reserved for the luggage compartments and toilet. Consequently, the chassis frame should be designed not only to improve the performances of the bus but also to meet the functional requirements.

Ground structure approach is widely employed in simultaneous topology and sizing optimisation of discrete structure. The ground structure determines the design space of the optimisation. Therefore, defining proper ground structure is a key point to satisfy the functional requirements. Generally, topology optimisation and sizing optimisation share one ground structure. Nevertheless, in order to satisfy the functional requirements on engineering products, not all beams should engage in the topology optimisation. Likewise, sizing optimisation should not be performed on these beams given specially shaped cross-sections for installation. Hence, an independent ground structures strategy is presented, where different ground structures are defined for topology and sizing optimisation.

First of all, based on the original chassis, 88 diagonal beams are added to the area of passenger seat floor and luggage compartment floor to form a whole structure as shown in Figure 2 (a). To be specific, in the whole structure, it must be guaranteed that no beams go across the spaces for luggage compartment etc.

Then, part of beams in the whole structure participate in the topology or sizing optimisation. Topology optimisation changes the layout of the structure significantly. In order to avoid the change of the overall architecture of the chassis frame, 90 diagonal beams, 41 longitudinal beams, 42 cross beams and 7 vertical beams are selected from the region of the passenger seat floor and luggage compartment floor to form the topological ground structure (TGS) as shown in Figure 2(b), in which beams in the TGS are in red color. Besides those beams with specially shaped cross-sections, all beams in the whole structure are chosen to compose the sizing ground structure (SGS) which are outlined in red in Figure 2(c).

Essential functional constraints are satisfied via constructing proper whole structure and ground structures before the optimisation. With the introduction of IGS, it is more flexible to choose suitable design spaces for topology optimisation and sizing optimisation.



(a) Whole structure (b) Topological ground structure (TGS) (c) Sizing ground structure (SGS)

Figure 2: Whole structure and ground structures of the chassis frame

5.2. CCGA

The FE model of the chassis frame is created with thousands of beam elements. Each beam in the TGS has a topological variable, and each beam in the SGS has a sizing variable. The number of design variables in the simultaneous topology and sizing optimisation is very large. Therefore, a cooperative coevolutionary genetic algorithm (CCGA) is introduced to divide the complex search space into smaller spaces.

Decomposition and collaboration are two key features for CCGA architecture. Decomposition describes how to divide the variables into subpopulations. The design variables in this research are decomposed in a natural way, in which the topological variables and sizing variables are assigned into two subpopulations which evolve independently and concurrently. Meanwhile, the interaction between the two subpopulations happens during iterations, which is the process of collaboration. In order to evaluate an individual in one subpopulation, it is necessary to select a representative from the other subpopulations to form a complete solution. The best individual in the other subpopulation is chosen as the representative in this paper.

With CCGA, topological variables and sizing variables evolve in two different GA systems. Hence, it is possible to choose different optimisation parameters according to the features of topology optimisation and sizing optimisation.

IGS is employed in the preparation stage, while CCGA is utilized in the process of optimisation. Both provide topology optimisation and sizing optimisation with independence. Therefore, it is natural to integrated IGS and CCGA together.

6. Implementation

6.1. Formulation

The objective is to minimize the mass of the bus body frame. The performances of the bus body frame including the torsional stiffness, the foundational frequency and the max Von Mises stress under full-loaded bending case are constrained to be no worse than the original bus body frame. Symmetry and consistency constraints are two types of manufacturing constraints included in this research. Symmetry constraint, which requires the topology/cross-section of beam elements in the TGS/SGS to be symmetric about a line or a plane, is helpful to reduce the number of variables, lower the manufacturing cost and improve the aesthetic feature. Consistency constraint divides the beam elements in the TGS/SGS into groups, and the topological/sizing variables of those beam elements in a group are supposed to have the same value. Consistency constraint is taken into consideration for two reasons: first, during FE modelling, a beam is usually modelled with several elements, so consistency constraint is applied on these elements to make sure that the beam is deleted or retained entirely and the cross-section is consistent along the beam; second, relative beams in the structure are required to be consistent for the same purpose as the symmetry constraint. The formulation of simultaneous topology and sizing optimisation of the bus chassis is as follows:

$$\begin{cases} \min\ m \\ \text{s.t.}\quad K_\Psi / K_\Psi^0 - 1 \geq 0 \\ \qquad f_1 / f_1^0 - 1 \geq 0 \\ \qquad \sigma_{\max} / \sigma_{\max}^0 - 1 \leq 0 \\ \qquad t_i = t_j, (i,j) \in SymT \cup ConT \\ \qquad x_i = x_j, (i,j) \in SymS \cup ConS \\ \qquad t_i \in \{0,1\}, i \in T \\ \qquad x_i \in X, i \in S \end{cases} \tag{2}$$

Where m, K_Ψ and f_1 are the mass, the torsional stiffness and the fundamental frequency of the bus body frame with the new chassis frame respectively, and K_Ψ^0 and f_1^0 are the torsional stiffness and the fundamental frequency of the original bus body frame; σ_{max} and σ_{max}^0 are the max Von Mises stress under full-loaded bending case of new and original bus body frame respectively; t_i and x_i are the topological variable and the sizing variable of the i^{th} beam respectively; *SymT* and *SymS* represent the sets of members required to be symmetric in the TGS and the SGS respectively. *ConT* and *ConS* represent the sets of members required to be consistent in the TGS and the SGS respectively; T and S correspond to the sets of members in the TGS and the SGS respectively; the cross-sections of the beams must be selected from an available set, and X is the set of property IDs corresponding to the available cross-sections. Table 3 shows the available square and rectangular cross-sections in this research.

Table 3: The set of available cross-sections

Property IDs (PID)	1	2	3	4	5	6	7	8	9	10
Width (W) / mm	20	20	20	30	30	30	40	40	40	50
Height (H) / mm	20	30	40	30	40	50	40	50	60	50
Thickness (T) / mm	2	2	2	2	2	2	2	2	2	2

6.2. Optimisation parameters

After grouping, there are 112 topological variables and 70 sizing variables. A topological variable can be 1 or 0, and a sizing variable can be 1 to 10. Therefore, the design spaces for topology optimisation and sizing optimisation are 5.19×10^{33} and 1×10^{70}, respectively. Due to the great distinction between the design spaces, the population sizes for topological subpopulation and sizing subpopulation are set differently, which are 150 and 250 respectively. The probabilities of the crossover and the mutation are 0.8 and 0.05 respectively. The tournament selection is utilized, and the tournament size is 2. The optimisation is terminated when the generation reaches 250.

6.3. Automatic reloading
Many beams of the chassis frame bear uniformly distributed loads such as passenger seats, luggage and so on. Generally, beams with loads cannot be deleted during optimisation. However, the design space of topology optimisation would be very limited if those beams are kept mandatorily. In order to tackle this conflict, the uniformly distributed loads are reloaded according to the new topology of the chassis frame. Unlike concentrated load applied on a specific node, the uniformly distributed loads are beared by a region of beams. When some beams in the region are removed, the loads are reloaded automatically on the retained beams so that the removed beams do not bear any loads and the total loads applied uniformly on the retained beams remain unchanged.

7. Results
The performances of the original bus and the optimal bus are listed in Table 4; compared with the original bus, the mass reduces by 246.45 kg (8.42% of the original bus), while other performances are not worse. Figure 3 depicts the topology of the optimal chassis, in which retained beams in the TGS are marked in red including 25 diagonal beams, 5 longitudinal beams, 22 cross beams and 7 vertical beams. For comparison, the topologies of the region F1 and F2 (see Figure 3) in the optimal chassis and the original chassis are given in Figure 4(a) - (d) respectively. Compared with the original chassis with 2 diagonal beams, 41 longitudinal beams, 40 cross beams and 7 vertical beams in the TGS, diagonal beams are preferred, longitudinal beams are reduced significantly and close to half of the cross beams are removed from the TGS of the optimal chassis.
Figure 5(a) - (i) illustrate the cross-sections selected by the beams, in which the beams with the cross-sections indicated in the captions are marked in red. Referring to the figures, relatively small cross-sections (PID 1-3) are mainly employed in the diagonal beams in perpendicular direction and the longitudinal beams; medium-sized cross-sections (PID 4-6) are principally selected by the small span diagonal beams in the region of floors and the vertical beams; large cross-sections (PID 7-9) are less adopted, which are chiefly used in long span diagonal beams in the region of floors and reinforced beams in the installation area of the rear axle.

Table 4: The performances of the original bus and the optimal bus

Model	Mass / kg	Torsional stiffness / kNm•(°) $^{-1}$	Fundamental frequency / Hz	Max Von Mises stress / MPA
Original bus	2926.34	39.88	7.67	158
Optimal bus	2679.89	39.89	7.70	158

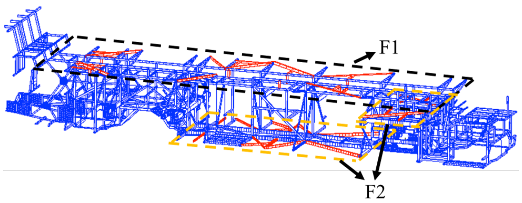
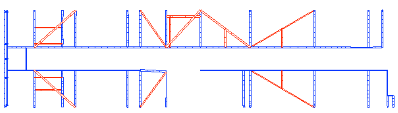
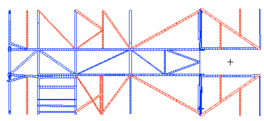


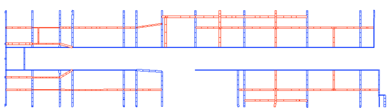
Figure 3: Topology of the optimal chassis



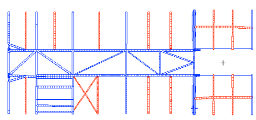
(a) Top view of F1 in the optimal chassis



(b) Top view of F2 in the optimal chassis

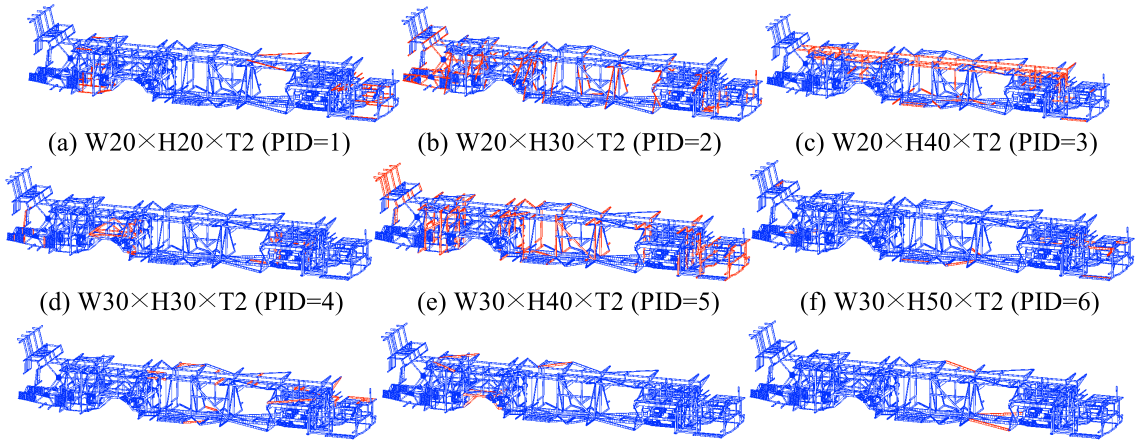


(c) Top view of F1 in the original chassis



(d) Top view of F2 in the original chassis

Figure 4: Topologies of F1 and F2



(a) W20×H20×T2 (PID=1) (b) W20×H30×T2 (PID=2) (c) W20×H40×T2 (PID=3)
(d) W30×H30×T2 (PID=4) (e) W30×H40×T2 (PID=5) (f) W30×H50×T2 (PID=6)
(g) W40×H40×T2 (PID=7) (h) W40×H50×T2 (PID=8) (i) W40×H60×T2 (PID=9)

Figure 5: Cross-sections of the optimal chassis

8. Conclusion

An architecture of CCGA-IGS was put forward for simultaneous topology and sizing optimisation of an integral bus chassis. In the preparation stage, additional beams were added to the original chassis to form a whole structure, and then different set of beams were chosen from the whole structure to construct ground structures for topology optimisation and sizing optimisation respectively, namely the process of the IGS strategy. The pre-defined functional requirements are guaranteed in this stage. Variables were grouped according to symmetry and consistency constraints to decrease the number of variables and satisfy the manufacturing constraints. Then, in order to overcome the hindrance of large number of design variables, CCGA was introduced to solve the problem, in which topological variables and sizing variables were divided into two subpopulations that evolved in two different GA systems. During the optimisation, the uniformly distributed loads on the chassis frame were reloaded in accordance with the topology of the newly generated chassis.

The bus body frame with the optimal chassis is significantly lighter than the original bus body frame, while the torsional stiffness, the foundational frequency and the max Von Mises stress are not worse. Meanwhile, the optimal chassis satisfies the functional and manufacturing requirements considered in this paper.

9. Acknowledgements

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10. References

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