# DESIGN OF A MULTI-FUNCTIONAL SEMITRAILER USING STRUCTURAL SANDWICH PANELS

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**SUMMARY**: Due to economic development within the European community the amount of transported load will grow substantially within the next 15 years. Since road transport comprises 75% of the total transport, the growth will result in an increase of transport by road of 25%. This increase, however, is in conflict with our growing environmental awareness. Therefore, in order to decrease the emission of $CO_2$ and $NO_x$, there is a need to increase the maximum pay-load and, at the same time, increase the utilisation of a tractor-semitrailer combination. The pay-load increases by lowering the net tare weight (for weight based transport) or increasing the inner volume (for volume based transport). With a multi-functional semitrailer the chances of an empty return are minimised, and subsequently the utilisation increases. A sandwich based chassisless design concept shows that it is possible to increase the pay-load and utilisation simultaneously without a drastic increase of the costs.

**KEYWORDS**: transport vehicle, foam-cored sandwich structure, lightweight, trailer

## INTRODUCTION

At this moment road transport comprises about 75% of the total transport of goods. Despite of all developments in transport by rail and over water most of the economic growth will result in an increase of road transport of 25% and, consequently, increase of number of vehicles [1, 2]. The most obvious way to increase the possible transport by road is to increase the number of goods per ride. However, the dimensions and maximum allowable weight are within the EC strictly ruled [3]. Therefore, possible solutions to increase the amount of goods per ride need to be sought within the design of the tractor-trailer combination.

Up to now, the increase of road transport combined with a high competitive European market led to three innovations in transport vehicles; (i) vehicles with a minimum net tare weight, (ii) vehicles with a maximum inner volume, and (iii) multi-functional vehicles. The first and second increase the capacity and the third innovation, multi-functionality, increases the utilisation of the capacity of the semitrailer. Unfortunately however, the innovations presented by the manufacturers are based on their present design and, therefore, lead to higher priced semitrailers. Furthermore, a present closed box semitrailer optimised in net tare weight has, as a consequence, a reduced inner volume and functionality, and vice versa.

In line of the presented innovations, it was the objective to design a closed box semitrailer optimised in weight, volume and multi-functionality (to increase the degree of utilisation), avoiding a drastic price increase. A decrease of the net tare weight and increase of inner volume will increase the maximum pay-load in mass and volume based transport, respectively. When on top of the increase in pay-load the utilisation is improved, the average actual pay-load of the semitrailer significantly increases. This increase in utilisation is found in the multi-functionality of the semitrailer, i.e. the semitrailer can be deployed in various kinds of transport (mass and volume based). For example a common load from north to the south of Europe is meat (pork and veal). In reverse way, fruit or clothing is most common. A semitrailer that can transport both meat and clothing has the ability to be nearly 100% utilised. At present the utilisation in international transport is approximately 60% [1,2]. In national transport the utilisation is only 50% due to just-in-time deliveries. In case of seasonal transport, the advantages of a multi-functional design are evident.

In order to reach these objectives (lightweight, high volume and multi-functionality) a new lightweight innovative design concept based on a self-supporting box structure is essential. In such a design the box itself rather than a chassis forms the load-bearing component. In this study lightweight structural foam-cored sandwich panels, which are connected by fibre reinforced pultrusion profiles are used for such a monocoque concept. The panel design is governed by its stiffness and (core) insulating properties. By reducing heat-bridges, the thickness of the panels is minimised. Hence, the inner volume is maximised. Besides the insulating properties of the closed box structure for (i) conditioned transport, the design is suitable to (ii) airfreight containers with the integrated handling system, (iii) hanging garment and (iv) double stocked goods.

## CURRENT SEMITRAILER CONCEPTS

The present available closed box semitrailers can be subdivided into two categories, the conventional chassis based and chassisless semitrailers. In most of today’s semitrailers a heavy steel chassis forms the load bearing structural part (Fig. 1a). The mounted box of a chassis semitrailer consist of mainly non-structural materials, like for instance plywood and low fibre volume fraction GFRP sheet. Consequently, the closed box does not contribute to the stiffness and strength of the semitrailer [4]. The floor of a chassis concept consists of steel beams with on top a heavy wooden floor. The steel beams, transversely placed, are connected to the steel chassis. For conditioned transport the box has an insulation value of less than 0.4 $W/m^2K$ to answer the FRC-certification [5] and has, therefore, foam cored sandwich walls and a roof with non-structural GFRP or wooden outer-skins. The insulated floor is, subsequently, built up from a foam core with wooden faces.

A small number of today’s semitrailers are chassisless semitrailers. In a chassisless concept, the closed box forms the load bearing structural component (Fig. 1b). Therefore, the materials used in the box of a chassisless semitrailer are structural materials like at best aluminium sheets riveted onto aluminium profiles for the wall [6]. As for a chassis semitrailer, the floor of a chassisless semitrailer is built up from steel or aluminium beams placed in transverse direction with a wooden floor on top. In this modular built up the separate panels are bolted together. Around the axles, an axle frame divides the peak forces over several transverse beams. In case of conditioned transport, the insulation foam is bonded with a structural sheet on the outside and covered with a non-structural glass-polyester skin from the inside. As in the chassis based concept, the insulation of the floor of the chassisless concept is a panel with wooden faces.

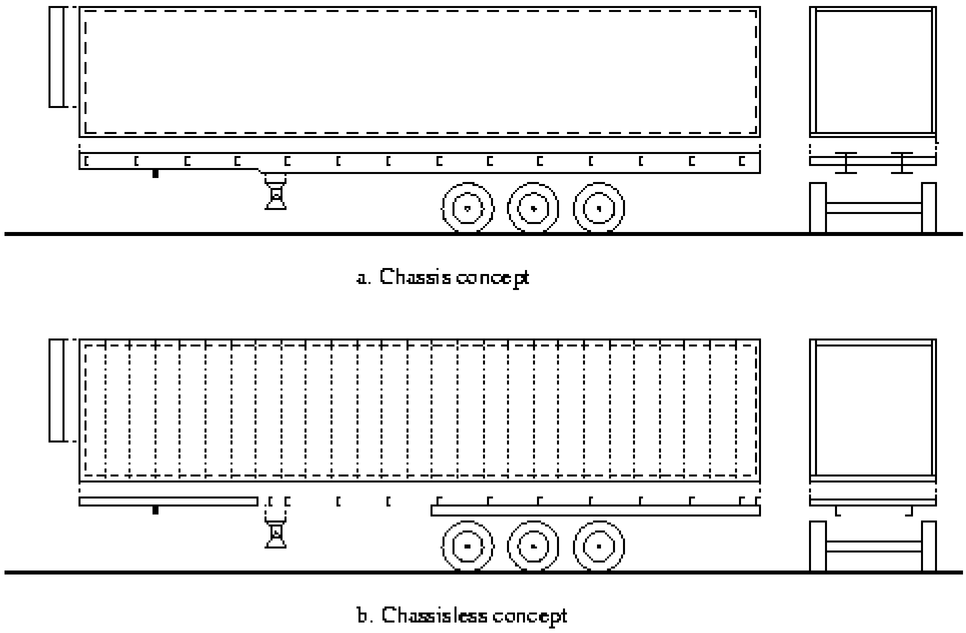


*Figure 1: Presentation of the conventional (a) chassis and (b) chassisless concept for a triaxle insulated closed box semitrailer. At front the cooling unit is situated.*

In both concepts the attachables, axles and kingpin are all connected to either the high steel chassis, the axle frame or transverse beams. In Table 1 the features of the chassis and chassisless concept are presented. The initial cost of the chassisless concept is approximately 5000 Euro higher, but due to lower running costs the return of investment time could be less than 2 years. For both designs the highest contribution to the weight has the floor panel and chassis/axle frame, 38% (3800 kg) in the chassis concept and 30% (2500 kg) in the chassisless concept. For weight reduction one should therefore focus on the chassis/axle frame and floor of the present available semitrailers.

*Table 1: Listing of features of the various semitrailers; the chassis, chassisless and multi-functional concept (at 150.000 km/year)*

| **Feature per unit** | | **Type of semitrailer** | |
|---|---|---|---|
| | | **Chassis** | **Chassisless** |
| Initial costs | [Euro] | 40.000 | 45.000 |
| Weight | [kg] | 10.000 | 8.500 |
| Inner volume | [$m^3$] | 85 | 90 |
| Maintenance/Repair | | - | + |
| Revenue | [Euro/year] | 120.000 | 123.000 |

Since the inner height of the semitrailer is determined by the thickness of the floor panel above the fifth wheel of the tractor (the coupling section), the chassisless semitrailer has a higher inner volume than the chassis concept. This is caused by the load distribution from kingpin over the self-supporting box structure in the chassisless concept. The maintenance and repair costs of a chassisless concept are small. First of all due to the modular construction, the panels are easily disconnected, and secondly because the floor and side walls are built up from small segments, which are easily replaced. Moreover, small repairs and maintenance can be performed in almost all transporter workshops.

## DIMENSIONS AND FUNCTIONALITIES OF THE NEW DESIGN

Before starting the new design based on structural sandwich panels, one has to decide upon the outer and inner dimensions of the semitrailer. These dimensions are highly depending on the functionalities that need to be incorporated in the design, the type of wheels used and the height of the fifth wheel of the tractor. The outer dimensions of a tractor-semitrailer combination are strictly ruled and as a consequence the width, height and length of a semitrailer are set (2600 x 4000 x 13600 mm, respectively). The smallest height of the fifth wheel is 920 mm [7] and smallest standard available wheels have a diameter of 780 mm. With a minimum space above the wheels of 70 mm, the resulting free height underneath the semitrailer is 850 mm.

For a closed-box semitrailer suitable for conditioned transport the insulating value (K-value of 0.4 $W/m^2K$) will be set by thickness and type of foam used in the sandwich panels. First hand calculations where used to estimate the minimum thickness for insulation of all panels. In Table 2 the thickness of panels, used insulating core material and resulting inner dimensions are presented.

*Table 2: The thickness of panels and resulting inner dimensions to fulfil the FRC requirements.*

| Panel / Inner dimension | Core material | Thickness/Length [mm] |
|---|---|---|
| Floor panel | PVC foam | 120 – 190* |
| Side wall | PU foam | 50 |
| Roof panel | PU foam | 100 |
| Front wall | PU foam | 200** |
| Doors | PS foam | 100 |
| Inner length | | 13400 |
| Inner width | | 2500 |
| Inner height | | 2860 |
| Inner volume | | 95.8 $m^3$ |

* The thickness of the floor panel at the coupling section is 120 mm. Behind the coupling section the thickness is 190 mm.

** Average thickness of front wall. Minimum and maximum thickness of front wall is 72 and 540 mm, respectively (ISO 1726).

Apart from the insulating requirements the design is influenced by the functionalities incorporated in the design. An added restriction to the functionalities is the net tare weight of the closed box semitrailer, which should be below 7500 kg including all attachments, cooling unit, etc. The consequences of each functionality is listed:

- *conditioned transport;* the dimensions mentioned above and placement or integration of cooling unit in front wall.
- *airfreight container transport;* for (un-)loading of airfreight a handling system is integrated in the floor panel.
- *hanging garment;* flexible system giving the possibility to attach bars for hanging garment from wall to wall. Walls should be capable for carrying load.
- *double stocked goods;* flexible system to attach bars from wall to wall (similar to hanging garment). Walls should be designed for carrying the second floor load.

## STRUCTURAL DESIGN OF THE PANELS

The chassisless design is based on the contribution of structural components of the closed box to the overall stiffness and strength of the semitrailer. The separate structural foam cored sandwich panels are connected into a self-supporting box structure. In a chassisless semitrailer the forces from kingpin to axles is transferred by the box itself, where in a chassis concept the chassis takes up and distributes the load. During the design process it appeared that the structural design is governed by the design requirements of the separate panels. When the separate panels are forming a closed box the behaviour will fulfil the design requirements of the closed box. Therefore, the design is split in two. First the stiffness of the separate panels is estimated, which leads to the thickness and choice of materials in the facings of the foam cored sandwich. In the next paragraph the modular self-supporting box will be analysed.

For determining the stiffness of the sandwich panels a relative simple model is composed of 4 node thick shell elements. By using the composite material property option, the foam-cored sandwich is easily modelled [8]. The total deflection in bending and shear is of interest when the design is governed by deflection (see Table 3). In this so-called ‘stiffness based design’ the shear deflection in the weak foam core becomes dominant. Therefore, the transverse shear option during the finite element analysis (FEA) is taken into account.

*Table 3: Panels requirements for design.*

| Panel | Load [kN] | Representing load situation | Max.deflection [mm] |
|---|---|---|---|
| Floor: floor | 400 | Weight of semitrailer & pay-load | 20 |
| kingpin area | 120 | Static load, fifth wheel | 20 |
| axle area | 270 | Static load, triaxle | 15 |
| Side wall | 70 | Wind load | 40 |
| Roof | 20 | Snow or wind load | 30 |
| Front wall | 75 | Moving goods | 30 |
| Doors | 38 | Moving goods | 30 |

Due to the sandwich built up the required stiffness of both the coupling (kingpin) section and the axle frame are much smaller compared to the present built up. The conventional chassisless concept only distributes the loads at kingpin and axles from wall to wall. With the sandwich built up the loads are divided over the entire panel and it will therefore be possible to reduce the weight and stiffness of the panels. Moreover, in the present chassisless concept with the use of steel, the design of the highly loaded parts is based on strength. Hence, the application of aluminium and/or fibre reinforced materials as a facing material becomes justifiable.

## STRUCTURAL DESIGN OF THE BOX

A self-supporting box structure based on sandwich panels will require reinforcements at the corners, the kingpin section, the feet, the triaxle, the cooling unit and the doors. In the design these reinforcements can be; (i) integrated in the design, (ii) necessary for assembling pieces or (iii) connected to the finished box structure. During the analysis of the separate panels, however, these reinforcements are neglected but are in the FEA of the entire closed box modelled in the sandwich panels. Also in this model the elements are 4 node thick shell elements. Again during the analysis the composite and transverse shear option is used. In the design the peak forces in the floor panel are distributed evenly over the floor panel in such a manor that the wall panel does not require local reinforcements. For simplicity of the design, the local reinforcements in the floor panel are placed in the core of the sandwich panel.

Various load conditions are applied during the analysis. In the case of a uniform distributed load of 400 kN on the floor panel and 70 kN on the side walls the deflection in the middle of the box is less than 16 mm. Approximately 10 mm of this deflection is caused by the deflection of the floor panel itself. The deflection of the side wall is approximately 20 mm in the middle of the panel. In the case of a box structure all deflections are less than the design requirements for the separate panels, due to the contra moment acting in the corners. Except for the axle frame and coupling section the stresses are low and again show that the design is stiffness based. The built up of all panels is presented in Table 4.

*Table 4: Built up of all panels.*

| **Panel** | **Built up off all panels from the in- to the outside of the semitrailer (thickness [mm])** | | | | |
|---|---|---|---|---|---|
| Floor: floor 120 mm | Plyw (12) | Alu (3) | PVC50 (95) | GFRP (10) | |
| floor 190 mm | Plyw (12) | Alu (3) | PVC50 (172) | GFRP (3) | |
| kingpin area | Plyw (12) | Alu (10) | GF130 (90) | Steel (8) | |
| axle area | Plyw (12) | Alu (3) | PVC50 (172) | GF130 (158) | Steel (5) |
| Side wall | Alu (2) | PU40 (48) | GFRP (2) | | |
| Roof | GFRP (0.5) | PU40 (99) | GFRP (0.5) | | |
| Front wall 72-540 mm | GFRP (2) | PVC40 (68-536) | GFRP (2) | | |
| Doors | GFRP (2) | PVC40 (96) | GFRP (2) | | |

Plyw: Plywood, Birch triplex. Alu: Aluminium, alloy 5454.
Steel: condition Fe 430. GFRP: Glass fibre reinforced plastic, quasi isotropic laminate.
PVC40: PVC-foam, density 40 kg/m$^3$. PVC50: PVC-foam, density 50 kg/m$^3$.
PU40: PU-foam, density 40 kg/m$^3$. GF130: PVC-foam, density 130 kg/m$^3$, reinforced with GFRP.

**Floor panel:** As mentioned earlier, local reinforcements in the floor panel are necessary for introduction and even distribution of forces over the box structure. These local reinforcements are inserted either by changing the foam core or by the integration of corrugated glass-fibre-reinforced laminates, which connect top and bottom skins of the sandwich. Local reinforcement of the foam core can be done by increasing the foam density. However, only in the case of an integrated fibre reinforced corrugated structure the shear strength of the sandwich panel will increase dramatically, while still avoiding large heat bridges (Fig. 2). Basically, the shear deflection is reduced because the shear forces are taken up by the GFRP and consequently the shear stresses in the foam core are reduced. The most important part of the floor panel with the highest shear forces is the coupling section. This part must be designed for the introduction and distribution of a static point load of 12 tonnes. During transport this load can almost double. This section has therefore both an increased foam density and local

GFRP reinforcement. Instead of conventional hand lay-up the current floor panel design has to allow for the use of more automated manufacturing processes like the vacuum assisted resin transfer moulding (VARTM) process [9]. In the VARTM process the dry fibres are impregnated under vacuum. Due to the vacuum, the process only requires a cheap single sided mould and a vacuum bag. In comparison with the hand lay-up method, the VARTM process is less labour intensive, gives better composite properties (higher fibre volume fraction), and has better repeatable quality.

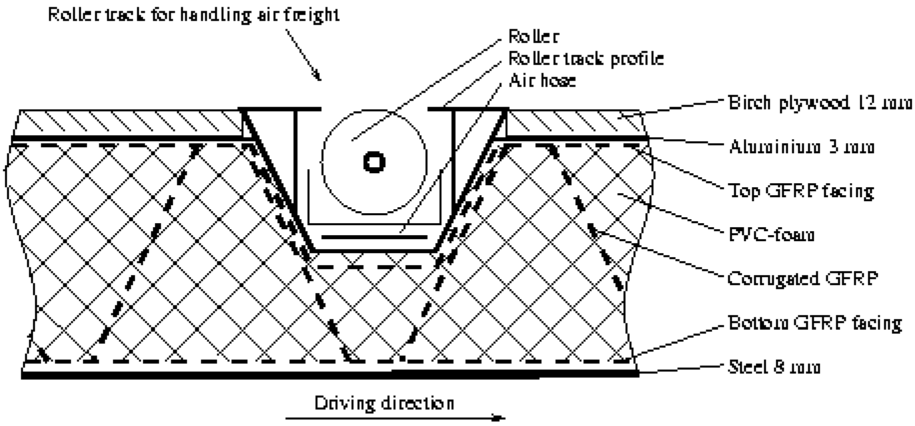


*Figure 2: Schematic cross-section of the corrugated GFRP reinforcement of the PVC-foam core at the kingpin section.*

As mentioned earlier, for simplicity of the design the lay-up of the coupling section in the area of the kingpin is similar to the lay-up used for the floor panel. The top layer is 12 mm of plywood (Fig. 2), placed in between the roller tracks used for the air-freight pallets. Over a length of 1080 mm the thickness of the aluminium sheet is 5 instead of 3 mm. The PVC-foam core is reinforced with a GFRP laminate with a quasi-isotropic lay-up (E=15 GPa). In the current preliminary study the entire design is based on this laminate and no further optimisation has been carried out. However, it is clear that further optimisation by using different configurations, anisotropic fibre lay-ups and/or the use of other advanced fibres should be explored. For the aluminium skins the alloy 5454 is chosen (maximum design stress of 200 MPa).

**Walls:** When the floor panel is designed to distribute the peak forces at the axle frame and coupling section evenly, local additional reinforcements in the wall (and subsequently the roof) panel are not required. As a consequence, both side walls and roof panel have a constant thickness of facings and core material, which allows for the use of fairly simple automated, and hence less costly, manufacturing processes. The thickness of the side wall is at maximum 52 mm, leaving an inner width of 2496 mm. Local buckling of side walls at the position of the kingpin and axles is avoided with the even distribution of the peak forces over the floor panel [10, 11]. Resulting stresses in the side wall are, therefore, small. For transportation of hanging garment and placing a second floor, provisions for inserting bars from wall to wall are included. The front wall fits the radius of 2.040 mm (ISO 1726) from centre kingpin to the front of the semitrailer. With the integration of the cooling unit in the front wall the weight is reduced.

**Roof panel:** The deflection of the roof panel under a load of 0.5 kPa is approximately 10 mm. Both the stresses in the thin GFRP faces are at maximum 9 MPa. The low stresses show again that the design is based on stiffness. In a chassisless concept the main contribution of the roof panel to the self-supporting structure is to maintain a constant distance between the side walls, i.e. to keep the side walls in plane.

**Doors:** In most of the present doors the looking bars are attached to the doors. In a few designs, the looking bars are placed in the doors. In such a case the doors can either be placed approximately 40 mm backwards or can be made 40 mm thicker without loosing inner length. The first option gives a higher inner length and the second gives better insulating properties and is, therefore, chosen.

## ANALYSIS OF THE BOX

The proposed design is numerically analysed using FEA. The floor panel is divided into 11 different section. This is mainly caused by the difference in thickness of the floor panel and reinforcements at the kingpin section, trailer feet, axles and rear frame. The model is loaded under various conditions, first supported at the kingpin and axles, and secondly at the trailer feet and axles.

**Resting on kingpin and axles:** Numerical analysis shows that the maximum deflection of the semitrailer under a load of 70 tonnes, evenly divided over the floor surface, is 16 mm in the middle of the semitrailer and 6.5 mm at the side wall (Fig. 3). The floor panels deflection is consequently 9.5 mm (16-6.5). The deflection of the side wall under an uniformly distributed load of 6 tonnes is 20 mm in the middle of the panel. Part of this deflection is caused by the displacement of the roof panel. As indicated earlier the high peak forces at kingpin, trailer feet and axles are possible threats for buckling of the side walls. Buckling of the side wall will instantly lead to total failure of the self supporting box structure. Therefore, the stresses in faces and core of the side wall are important [10, 11]. The maximum stress in the aluminium layer at the inside of the wall panel is 19 MPa. This stress is found in the mid-section, between the coupling section and the axles frame. In the GFRP laminate of the wall panel the maximum stress is 16 MPa. Shear stresses in the PU-foam core are low, less than 0.01 MPa, compared to the maximum shear strength of PU-foam with a density of 40 $kg/m^3$ (0.17 MPa). These low stresses in facings and core show that even under extreme load conditions local reinforcements in the side walls are not required, provided an adequate distribution of high peak forces in the floor panel.

**Resting on trailer feet and axles:** In the numerical analysis with the semitrailer resting on trailer feet and axles, the same load conditions are applied. The maximum deflection of the semitrailer is 13 mm, around the kingpin, and 3 mm at the side wall. Consequently, the deflection of the floor is 10 mm. In this analysis the stresses in the top and bottom layer of the floor panel are 20 MPa at the trailer feet. The maximum shear stress in the PVC-foam core is 0.3 MPa.

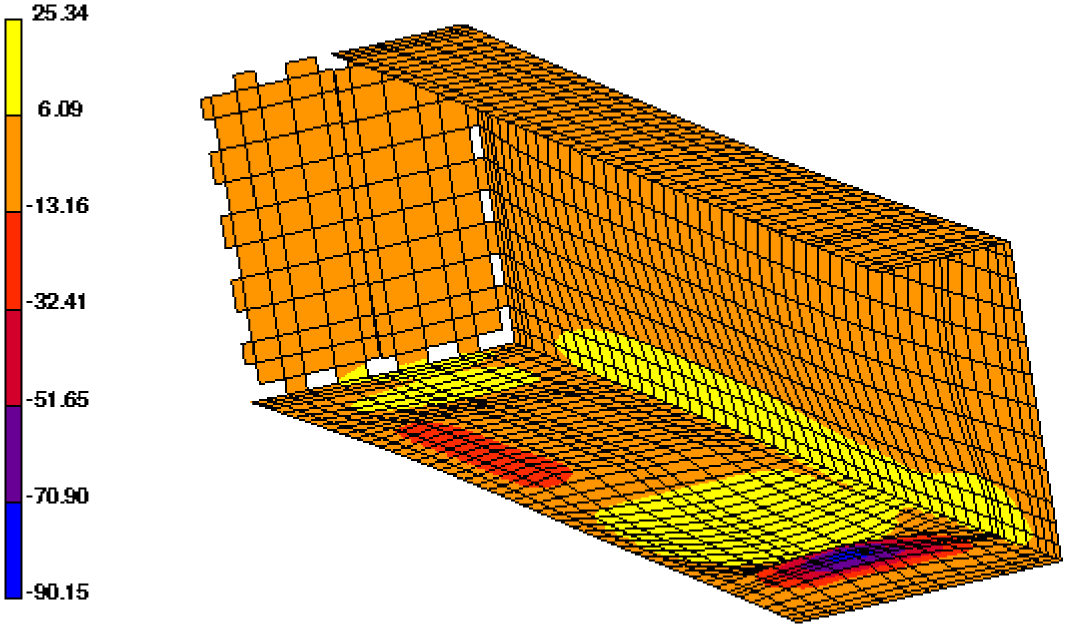


*Figure 3: Shape of deformed semitrailer loaded with 70 tonnes and resting on kingpin (tractor) and axles. For clarity the front wall, one side wall and half of the roof is not shown. Maximum stresses of the outer face in MPa.*

## FEASIBILITY

The general purpose of the innovations is to increase the average amount of transported goods per ride, and subsequently reduce the costs of transport. Inevitably the use of advanced composites will lead to a more expensive end-product. To minimise the price increase the costs of the production process of the semitrailer must be lowered. Therefore, the proposed concept should allow for the use of automated production technologies. This will lower the required amount of man-hours per semitrailer and a drastic price increase of a semitrailer is avoided (Table 6). A lightweight high volume multi-functional semitrailer can be used for almost all types of products that need or can be transported in a closed-box semitrailer. As a result, the transport business is given the chance to lower its costs of transport in terms of Euro's per load kilometre. Table 6 shows that the return-of-investment time of the new multi-functional design is compared with the conventional semitrailers less than two year.

*Table 6: Listing of features of the various semitrailers; the chassis, chassisless and multi-functional concept (at 150.000 km/year)*

| **Feature per unit** | | **Type of semitrailer** | | |
|---|---|---|---|---|
| | | **Chassis** | **Chassisless** | **Multi-functional** |
| Initial costs | [Euro] | 40.000 | 45.000 | 52.000 |
| Weight | [kg] | 10.000 | 8.500 | 7.000 |
| Inner volume | [$m^3$] | 85 | 90 | 95 |
| Maintenance | | - | + | - |
| Revenue | [Euro/y] | 120.000 | 123.000 | 130.000 |

## CONCLUSIONS

With the design of the multi-functional semitrailer it is demonstrated that simultaneously the following is optimised: (i) Weight: in comparison with the present chassis and chassisless semitrailer a weight reduction of respectively 2.9 and 1.4 tonnes is possible, down to 7.1 tonnes. (ii) Volume: Increase of inner volume of 10 and 5 $m^3$ in comparison with the present chassis and chassisless semitrailer, respectively. The inner volume of the proposed design is 95 $m^3$. (iii) Utilisation: An increase of the utilisation from 60% to 65% due to the multi-functional concept. Although, in the case of more automated manufacturing technologies like e.g. the VARTM process the number of production hours is reduced in comparison with the conventional labour intensive chassisless concept, the price is expected to increase due to the use of more expensive foam and fibre reinforced materials. However, the increase of pay-load and utilisation results in a return-of-investment time of less than two years. It is shown that the use of foam cored sandwiches can lead to a light-weight structural box with various integrated functions. These are a high volume, conditioned transport (FRC certified), second and third floor stocking of goods, and features which allow for the transport of e.g. flowers, hanging garment and air-freight pallets. The presented multi-functional design is in terms of strength (and stiffness) overestimated. The applied maximum displacement and deflections should, therefore, be reconsidered. Also the optimisation of the fibre direction in the composite layers will lead to a lighter concept, especially when the application of carbon or aramid fibres is analysed in detail. But then again it should be considered whether the weight reduction is in balance with the increase in material costs.

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