3DAYCar PROGRAMME

SPACEFRAMES

‘A study of an emerging body construction technology’

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Mr K. Sears Lotus Engineering, Norwich
Mr O. Stranberg Volvo Car Corporation, Sweden
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In the interests of continuous improvement the author welcomes any comments regarding the contents of this report and can be contacted at the address, e-mail or telephone number given on the front of this page.
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Executive Summary

- Around 95% of current automotive production worldwide uses the welded steel monocoque as the conventional form of body construction. It has provided an efficient and cost-effective means of volume production since the 1950s. The application of spaceframes also originated from around this time, in performance cars such as Lotus and Maserati.

- Monocoque is defined as a *structural skin* where outer panels (normally steel) are welded together early in production, contributing to the overall structural integrity of the vehicle.

- A spaceframe is defined where *non load-bearing panels are supported by a structural frame*. Body panels are attached or ‘hung’ on an extruded metal structure, offering greater flexibility in terms of production assembly and in the choice of materials, such as pressed steel, aluminium alloy or composite.

- VM’s are already diversifying in their approach towards body construction, away from conventional, welded steel monocoque. This is particularly the case in Europe where at least two-thirds of all VM’s are actively engaged in spaceframe development for elements of their range. Fiat is the most advanced, having recently announced that all future models will be based on semi-spaceframe structure pioneered by the Multipla.

- The key business drivers for Audi and Fiat in using spaceframes for the A2 and Multipla are low tooling costs, low weight, production flexibility and ease of model changes.

- Spaceframe construction and plastic panel technology must find the means of cost effectively increasing output to at least twice current levels, in order to approach the current economies of scale of welded steel monocoque.

- Developments such as solid-coloured plastic panels point towards significant changes in conventional automotive manufacture. As a result 12 hours or more of production order lead-time can be saved through the elimination of central Body & Paint shops.

- Spaceframe construction requires approximately a quarter more components during body frame construction and requires a high level of manual assembly. However, the net effect remains one of potential benefit to 3DC and order fulfilment where spaceframes can share extruded frame components across an entire range of model variants.

- Spaceframe production facilitates batch sizes of one; a particular challenge to conventional assembly where batches of identical body ‘attributes’ are required in order to satisfy line-based process requirements such as welding and painting. Spaceframes break this dependence on a pre-set assembly sequence where, in theory (assisted by the modular frame construction) any combination of model variants could be built to order.

- Significant development is expected in spaceframe construction during this decade. The author of this report supports the view that true flexibility and order fulfilment must stem from body construction itself, as opposed to merely re-configuring existing production, driven by radical changes to integral vehicle design and assembly.
1 Introduction

This report examines vehicle body construction in the automotive industry. It focuses on the emergence of spaceframes and the potential impact on vehicle manufacture and customer order fulfilment. Body construction today requires a high strength-to-weight ratio and rigidity, combined with cost effectiveness and ease of production. The welded steel monocoque has provided such a combination for volume production since the 1950's.

However, voluntary agreement with the EU on fuel efficiency savings which require lighter weight vehicles, increasingly competitive markets and rising environmental concern has forced vehicle manufacturers (VM’s) to reconsider current strategy. The questioning of mass production in favour of the adoption of JIT and Flexible Manufacturing Systems has been followed recently by significant levels of investment in alternative methods of alloy and composite body construction technology. This has resulted in a barrage of complex and confusing terminology, often used to describe similar design principles. This report aims to define the current state of body structure, and identify the implications for 3DayCar.

1.1 Objectives

The following represent the prime objectives of this report:

- To define the current state of spaceframe development in the context of European and Global automotive manufacture.

- To identify the key drivers of change in terms of automotive body construction today and in relation to 3DayCar.

- To compare the potential benefits to 3DayCar of the spaceframe over the welded steel monocoque in terms of production flexibility and reducing customer order lead-time.

- To examine what impact the introduction of spaceframes might have in relation to current & future platform strategy and the implications for 3DayCar.

1.2 Methodology

This report has been compiled from a combination of numerous e-mail exchanges, 10 telephone interviews, 4 site tours and an on-going review of current literature. A questionnaire was used initially to structure a number of interviews, but it was soon found that the limited number of respondents with direct experience of spaceframes favoured a broader approach to the study. The author is indebted to all those who provided much needed information on the subject and who freely offered their opinion. Industry publications such as Automotive News has filled a number of gaps and provided a sound background to the study.

Where specific information was required, the author has endeavoured to approach the individual concerned. However, in an industry where technology is inherently aligned to competitive advantage, it was found that product development data, particularly costs, was very difficult to attain. The table

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2 Automotive News, Detroit & Automotive News Europe, West Midlands: Crain Communications Inc
lists the key companies, vehicle models and sources consulted during the study.

<table>
<thead>
<tr>
<th>Model</th>
<th>Construction</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rover Salvo (Project)</td>
<td>Al. Spaceframe</td>
<td>Dr Kenneth Young, WMG, Warwick</td>
</tr>
<tr>
<td>GM Saturn</td>
<td>&quot;</td>
<td>Dr Frits Pil, IMVP.</td>
</tr>
<tr>
<td>Opel G90 (Concept)</td>
<td>&quot;</td>
<td>London Motor Show</td>
</tr>
<tr>
<td>Audi A2</td>
<td>&quot;</td>
<td>Mr Karl von Zengan, Audi, Neckarsulm</td>
</tr>
<tr>
<td>Nissan ALX</td>
<td>&quot;</td>
<td>Mr Kenneth Foxley, Nissan</td>
</tr>
<tr>
<td>Fiat Multipla</td>
<td>Steel Spaceframe</td>
<td>Mr Marco Vassallo &amp; colleagues.</td>
</tr>
<tr>
<td>Lotus Elise</td>
<td>Al ‘frame’</td>
<td>Mr Kenneth Sears, Lotus, Norwich</td>
</tr>
<tr>
<td>Opel Speedster</td>
<td>&quot;</td>
<td>London Motor Show (&amp; Auto. News)</td>
</tr>
<tr>
<td>Ford Fiesta</td>
<td>Steel Monocoque</td>
<td>Dagenham site tour</td>
</tr>
<tr>
<td>Volvo</td>
<td>Aluminium research</td>
<td>Mr Osten Strandberg, Volvo, Sweden</td>
</tr>
</tbody>
</table>

*Figure 1. Table to show sources of data used in this report*

### 1.3 Confidentiality

Whilst some of this report was produced using information freely available in journals and on the Internet, as a whole its contents should be considered confidential to 3DayCar. The author has been provided with specific details of VM product range and platform strategy and some discretion has been applied in deciding what should be included. Personal opinion from individuals, where appropriate and if permission has been granted, is recorded as such in the text, otherwise the outcome of any interview is generally reflected in the body of the report. The usual restrictions apply regarding access by companies or individuals outside the 3DayCar programme.
2 Alternative Body Technologies and the Spaceframe

This chapter defines the spaceframe and places it in context with other construction methods in use today. It compares current VM development that uses spaceframe related technology and concludes with a brief summary of the key issues.

2.1 Defining automotive body construction

Few automotive body structures represent a pure manifestation of a finite engineering principle. Similarly, the term ‘spaceframe’ seems to have been adopted by the automotive press and used to describe structures, which more accurately should be described as hybrids or ‘semi-structures’. Often in the build up to a new product launch, technological attributes are simplified by VM’s eager to capitalise on new technology, creating some popular misconceptions of basic technical terms. The following is given by way of an introduction into the current issues surrounding automotive body construction:

2.11 Chassis

The chassis was the most common type of structure used on the earliest cars of the 1900’s. Still used on trucks & lorries, Black-Cab taxis, and some off-road vehicles today, it provides a separate structural platform onto which is mounted a body. Two steel beams or box sections run down the entire length of the vehicle and are joined together by cross members, providing strength & rigidity and a low centre of gravity. The construction method of separate chassis and body has meant that this method is favoured by VM’s seeking an appropriate means of comparatively low volume, economical vehicle manufacture. Notable long running examples in the UK have been the Land Rover ‘Defender’ and the ‘Discovery’ series. An important derivative is the ladder chassis, commonly used in performance, combining a slim-line chassis with additional stiffening cross-members for a rigid, lightweight design.

2.12 Monocoque

The monocoque is currently the standard structure for most cars made around the world in high-volume (100,000+ per annum) production. Constructed from pressed sheet steel, it combines the function of both chassis and body in a three dimensional structure. In its purest sense, the term monocoque is applied to a structure which relies entirely on its outer skin for strength. Semi-monocoques have stiffening members and transverse frames supporting the skin or outer body panel and is the accurate term to use when describing the structure of most cars. Whilst some panels are detachable such as the doors, engine bonnet and the front wings, the remainder of the outside surface plays a key part in the structural integrity of the vehicle. With the exception of the Jaguar E-type, there are probably no true monocoques on the road today.

Figure 2: The welded steel monocoque, showing the large side pressing integral to its construction.
The monocoque originates from the work of Budd in the 1930’s who developed a separate, structurally independent body that sat on top of the chassis. As chassis and body began to develop as one unit, the increasing popularity of the design meant that the economies of scale required could only be achieved through the standardisation of parts and the high volume production of common steel pressings. The success of the ‘Buddist Paradigm’ lead to it becoming almost universal amongst volume VM’s by the 1960’s and little has changed to this day.

2.13 Spaceframe

Originally developed for performance cars such as Maserati in the early 1950’s, spaceframes resembled a ‘cage’ of welded tubes onto which a non-structural bodyshell was attached. The spaceframe, unlike the monocoque, relied on an internal tubular cage or frame to provide all the load bearing qualities of the vehicle. Colin Chapman with the ‘Lotus 8’ in 1955 developed an almost perfect lightweight spaceframe. However, in optimising the frame, access to areas such as the engine compartment became severely restricted.

On current models such as the Fiat Multipla, outside panels assist only in the crash worthiness of the structure, with the possible exception of the roof panel which provides some lateral stiffness. Current spaceframes can be constructed from either aluminium or steel extrusions and can readily take advantage of technology such as composite panels and high-strength adhesive bonding. Major savings can be achieved of around 30 to 40% in the frame weight.

Extrusions are an important feature of the spaceframe as they represent a departure from the reliance of conventional manufacture on pressed sheet steel as a means of achieving body stiffness and strength. The total tooling costs associated with either aluminium or steel extrusions in vehicle production are around half that of pressings.

Spaceframes are more labour intensive than the welded steel monocoque due a greater number of parts required in constructing the body. However, the arrival of the Multipla and Audi A2 challenges the generally accepted view of a technology associated with expensive, low volume cars. For the first time a structure very close to that of a true spaceframe is going to be used to build medium volume production runs of around 50,000 units a year.

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2.14 Composite

The term ‘composite’ is traditionally used in the automotive industry to describe the combination of two or more materials, usually involving plastics, such as glass reinforced plastic (GRP) or injection moulded thermo-plastics, in the construction of vehicle body parts. Until recently it was not strictly a means of body construction, as the composite body required a secondary structure such as a metal chassis or sub-frame to support it. However, it is included here to cover the growing list of vehicles whose construction cannot be adequately described using any one of the previous definitions.

Examples of such construction include the carbon fibre front body section of the Lotus Elise which connects with the two main side extrusions at the front of the load bearing frame, acting as a crumple zone and absorbing impact in the event of a collision.

The Daimler-Chrysler MCC Smart car is made up of external panels which, whilst not load bearing, are moulded from a colour-cored thermoplastic material developed specifically by GE Plastics. Perhaps the closest to true composite construction is the Chrysler Composite Concept Vehicle (CCV), launched in 1999. It is constructed entirely from a polyester based resin with no internal steel skeleton.

Large structural composites which are light and can be formed into complex shapes and can replace pressed metal parts. Until recently, panel rigidity, high cost and long manufacturing cycle times have limited their expectations in the industry. However, new moulding processes such as P4 are emerging, developed by USCAR in Ohio, where short glass fibre strands are sprayed by robots into a liquid resin. Composite construction is therefore felt to be an appropriate term, with applications extending beyond current use in plastic panels and bumpers. Whilst facing fierce competition from aluminium and steel producers, composites have significant implications for 3DC in the reduction of customer order lead time through the potential elimination of the conventional paint and body shop. This is discussed in more detail later.

2.2 VM spaceframe development

Section 2 of this chapter examines vehicles all of which incorporate the spaceframe principle in some respect, principally that of the load bearing frame with attachable panels. Accurately identifying spaceframe construction can be difficult: boundaries between one means of vehicular construction to another can be indistinct. The diagram in figure 4 below illustrates the authors view of the current inter-relationship between current vehicle construction methods.

*Figure 4: Diagram to show the inter-relationship between current vehicle construction methods.*
2.21 Lotus

Lotus in Norwich have pioneered the use of lightweight aluminium body structures, as epitomised by the Elise sports car. Whilst not strictly a spaceframe, the more technically correct ‘aluminium boxframe’ hardly does justice to the structural elegance of a lightweight frame that combines post-formed extrusions, folded alloy sheet and carbon-fibre sections. Whilst total annual production at Lotus (Elise and Esprit) is around 4000 units, half of the 1,900 employee’s on site are employed in the firm’s engineering consultancy business.

Lotus has recognised one limitation of the extrusion as being that it cannot utilise the ‘dead-space’ (eg the wheel arch) around the vehicle and its occupants to the same extent as a pressing. This means that opportunities for vehicle strengthening whilst not interfering with passenger space are lost. Some consideration by Lotus has been given to how extruded lengths could simulate the profile of a more conventional vehicle side-frame, in order develop products that cater not only for the weekend or ‘fun’ car market.

2.22 Daimler-Chrysler

DC has used plastic panels on a spaceframe-style construction on the Plymouth ‘Prowler’, a limited edition American replica ‘hot-rod’, produced in small quantities at around 2500 units per year. DC sources have been quoted as saying that the new Mercedes-Benz due in 2005, will have a full aluminium alloy chassis and body, but admit that the company lacks experience in aluminium car production processes.

2.23 General Motors

General Motors, in association with Alcan, described weight considerations as paramount during the development of the EV1 research vehicle. Constructed as a bonded/welded aluminium spaceframe, it weighs only 40% of an equivalent steel body. It combines three different types of composite to construct the roof and doors, the bumpers and the floorpan. Some of the principles of this vehicle were used in the Saturn: a volume production vehicle now offered to the public as a saloon or station wagon. Built in Tennessee USA, it uses a unique method of separately painting polymer panels which are then attached to a weld-intensive spaceframe during final assembly. There is an important principle illustrated here: whilst at first glance the Saturn body structure resembles a monocoque, consisting of pressed sheet metal parts, the use of detachable panels means that it cannot depend on the outside skin to be load bearing. Thus it must be included, at least in part, as incorporating some elements of spaceframe construction.

A recent concept car by GM Europe, the Opel G90, also features a spaceframe and continues the light-weight construction theme. Shown in Frankfurt in September 1999, the G90 was described by Opel’s Chairman as too costly to build on account of the company currently lacking expertise to manufacture an aluminium spaceframe. However, plans for an all-aluminium platform as the basis of almost all Opel’s models by 2005 has been outlined by the company, working with Norwegian alloy supplier Norsk-Hydro in order to meet future emission and fuel consumption standards.

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5 General Motors (1999) Company Report


Following collaboration between Opel and Lotus, the Speedster performance car will be put into production in low volume, at 4000 units a year and will use the same style of extruded aluminium alloy frame as the Elise.

It is interesting to note the reference to ‘lack of experience’ quoted here by DC and Opel where both have had aluminium spaceframe-style projects running since 1997. Reference by Opel was made to Audi as having a distinct advantage in being able to handle aluminium alloy in production given the launch of the luxury, low volume A8 model in 1994.

### 2.24 Audi

After the A8 was launched, all engineers and technicians involved in its developed were kept together to form the Audi Aluminium Centre in Neckarsulm. Consisting of around 100 personnel, the significance of lightweight, low cost production techniques was recognised and nurtured, culminating in the imminent launch of the A2 (Spring 2000). The A2’s aluminium spaceframe is 43% lighter than an equivalent steel structure, allowing new standards to be set for fuel economy.

As both the A8 and A2 are constructed from an aluminium extruded frame with sheet alloy panels, there has been significant technology cross-over since 1994. The A8 frame lengths are joined together at the spaceframe nodes by means of vacuum assisted die-castings. The vacuum action reduces any air bubble that may hinder welding. Experience has now shown that these castings can be larger, replacing sub-assemblies such as those around the B-pillar with a single component, as shown in the photo below.

![Figure 5: The Audi A2 spaceframe, showing the cast B-pillar.](image)

Joining technology has also been improved on the A2, with greater use of MIG welding, self-piercing rivets and laser welding: used to join difficult areas where there is only access on one side. The A8 is produced at a rate of around 75 units a day (15,000 pa) where 80% of the work is manual and 20% is automated. The A2 is expected to be produced in considerably higher volumes, around 50,000 per year.

Key factors in the development of the A8 and A2 was the recognition of the importance of lightweight, fuel efficient structures combined with low investment, extrusion based tooling. The future of aluminium alloy and spaceframe technology seems assured with the Audi Spaceframe or ‘ASF’ having been registered as a trademark by the company.

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8 Mr Karl-Heinz von Zengan, Audi Aluminium Centre, Neckarsulm, Germany. 20.10.99
2.25 Volvo

Volvo, Sweden, has set up a research workshop that is currently looking into all aspects of future vehicle construction. When asked for the key drivers of the research, the reply was weight saving in terms of fuel reduction and cost. Both monocoque and spaceframe were being considered, but the advantages of the latter were generally recognised as chiefly that of cheaper tooling. The potential disadvantages of spaceframes were currently seen as achieving similar volumes to that of conventional manufacture and keeping down the additional manual assembly cost content per vehicle.

2.26 Fiat

The steel spaceframe construction of the Multipla was driven by the need for low investment, more product differentiation and a shorter time to market. Attempting to target what they saw as a gap in the market for a small MPV, Fiat were unsure about its sales potential and required a low ‘break-even’ point of 40,000 vehicles a year. Using a welded frame of steel extrusions supporting steel body pressings, tooling costs are around half that of conventional manufacture.

High tensile steel rather than aluminium was chosen for the Multipla body because of the combination of ease of manufacture, repair and its relatively light weight. Whilst different from the Audi A2, the Multipla spaceframe still saves 30% in weight in comparison to a conventional structure.

Fiat has recognised the benefits of flexibility from the Multipla design, where body changes and model variations can easily be achieved by means of modification only to specific areas as required. Safety is not compromised as the structural efficiency of the spaceframe allows for important areas such as the passenger cell to be locally reinforced where necessary.

The company plans to standardise around 100 of the extruded components and share these amongst engineering platforms for the next generation of cars using a semi-spaceframe structure. This new platform concept, embodying the key elements of spaceframe technology learned from the Multipla, will be progressively applied to all new products including both niche market models and volume production. Assuming current production levels, this could effect the way over 2.5 million cars are built. Has Fiat started a move within the industry towards low investment, extrusion-based structures, as a novel type of advanced platform strategy?

2.27 Spaceframe development worldwide

Figure 6 overleaf summarises the current state of spaceframe development worldwide by manufacture and model. As this report is focused primarily on high volume production, it has included little on the aluminium spaceframe or full carbon fibre chassis development by Maserati and Ferrari (owned by Fiat). Whilst originating from 1950’s performance cars, the spaceframe is now re-emerging as a contender in mainstream vehicle body construction. It is perhaps appropriate therefore that the re-emergence of spaceframes is being lead in Europe. In North America, the number of examples is significantly lower. The Japanese, having evolved some of the most efficient means of making steel

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9 Mr Osten Strandberg, Volvo research, Sweden. 1.9.99
10 Mr Marco Vassallo, Technical Director, Turin, Fiat. 22.10.99
11 Mr Rosti, Senior Engineer, Turin, Fiat. 22.10.99
car bodies, view the shift from conventional monocoque into aluminium or composites with some trepidation.13

Figure 6: Table to show extent of spaceframe* development worldwide by manufacturer / model.

<table>
<thead>
<tr>
<th>RESEARCH</th>
<th>PROTOTYPE</th>
<th>PRODUCTION</th>
<th>LAUNCH</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EUROPE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RENAULT Espace</td>
<td></td>
<td>1984</td>
<td></td>
</tr>
<tr>
<td>VW AUDI A8</td>
<td></td>
<td>1994</td>
<td></td>
</tr>
<tr>
<td>FIAT Multipla</td>
<td></td>
<td>1998</td>
<td></td>
</tr>
<tr>
<td>PROTON Lotus Elise</td>
<td></td>
<td>1998</td>
<td></td>
</tr>
<tr>
<td>VW AUDI A2</td>
<td></td>
<td>1999</td>
<td></td>
</tr>
<tr>
<td>FIAT Ecobasic</td>
<td></td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>OPEL Speedster</td>
<td></td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>RENAULT Avantime</td>
<td></td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>FIAT Bravo / Brava</td>
<td></td>
<td>2002</td>
<td></td>
</tr>
<tr>
<td>VOLVO</td>
<td></td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>OPEL ‘Astra’ / G90</td>
<td></td>
<td>2005</td>
<td></td>
</tr>
<tr>
<td>DC MERCEDES ‘S-Class’</td>
<td></td>
<td>2005</td>
<td></td>
</tr>
</tbody>
</table>

| **NORTH AMERICA** |           |            |        |
| DC Plymouth Prowler |           | 1997       |        |
| GM Saturn |           | 1998       |        |
| GM / ALCAN EV-1 |           | -          |        |

| **JAPAN** |           |            |        |
| NISSAN AL-X |           |            |        |

Source: Auto. News +various. *Defined by the author as non-load bearing panels supported by a structural frame.

**Conclusion**

Around 95% of current automotive production world wide uses the welded steel monocoque as the conventional form of body construction. It has provided an efficient and cost-effective means of volume production since the 1950’s. Monocoque is defined as a structural skin where outer panels are welded together early in production, contributing to the overall structural integrity of the vehicle.

A spaceframe is defined as non load-bearing panels supported by a structural frame. Body panels are attached or ‘hung’ on an extruded steel / aluminium structure, offering greater flexibility in terms of production assembly and in the choice of materials such as pressed steel, aluminium alloy or composite. The concept of the spaceframe is not new and is now re-emerging in models in Europe such as the Multipla and A2 because of the potential to reduce tooling costs and lower body weight in order to increase fuel efficiency. Spaceframes offer significant benefits both to the future car industry as a whole and to the 3DC programme. The implications of these benefits are discussed in the following chapter.

3 Advantages and disadvantages: implications for 3DayCar

This chapter starts by comparing the potential benefits to 3DC of the spaceframe over the welded steel monocoque. It then examines what impact the introduction of spaceframes might have in relation to current & future platform strategy and the implications for 3DC.

3.1 Comparison of monocoque v spaceframe

The table below compares the key body construction attributes between the welded steel monocoque of the Fiat Marea with the extruded steel spaceframe of the Multipla. The Marea was chosen for its similar vehicle class and size to the Multipla. The table summarises the comparative issues that exist between the two methods of construction using current data from both models.

<table>
<thead>
<tr>
<th></th>
<th>Monocoque: Fiat Marea</th>
<th>Spaceframe: Fiat Multipla</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Body weight</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BIW</td>
<td>330 kg</td>
<td>253 kg (30% down)</td>
</tr>
<tr>
<td>Hang on</td>
<td>100 kg</td>
<td>102 kg</td>
</tr>
<tr>
<td><strong>Components</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>16</td>
<td>26</td>
</tr>
<tr>
<td>Sides</td>
<td>36</td>
<td>44 (total: 35% up)</td>
</tr>
<tr>
<td><strong>Tooling cost</strong></td>
<td>£200,000,000 approx*</td>
<td>£100,000,000 approx*</td>
</tr>
<tr>
<td><strong>Cost of body</strong></td>
<td>N/a</td>
<td>N/a</td>
</tr>
<tr>
<td><strong>Model changes</strong></td>
<td>Model variants limited to dimensions of the platform.</td>
<td>Model length &amp; width easily modified.</td>
</tr>
<tr>
<td><strong>EOS / ‘Break even’</strong></td>
<td>100,000 to 200,000 cars p.a.</td>
<td>40,000 – 50,000 cars p.a.</td>
</tr>
<tr>
<td><strong>Safety</strong></td>
<td>Multiple crash simulations per car</td>
<td>Simple crash testing</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body</td>
<td>Steel sheet</td>
<td>Steel extrusion (or aluminium)</td>
</tr>
<tr>
<td>Panels</td>
<td>Steel (or aluminium, composite)</td>
<td></td>
</tr>
<tr>
<td><strong>Assembly</strong></td>
<td>Welded together early in production</td>
<td>Panels attached separately</td>
</tr>
</tbody>
</table>

*Body weight' and 'Components' figures included by kind permission of Fiat Auto, Turin.  *Estimated figure

3.2 Body weight

Reducing vehicle body weight has a relevance to the 3DC programme that extends beyond the drive by the EEC to reduce emissions by encouraging the development of more lightweight, fuel efficient cars. Lighter cars rely less on additional features such as power steering, which in turn reduces overall load carrying requirements; thus setting in motion a cycle of weight-saving initiative and reducing vehicle complexity.

The Fiat Multipla saves 30% in the weight of its body-in-white (BIW) by using the steel framed spaceframe. Note, however, that the weight of the ‘hangs on’ (doors and bonnet) remain the same on account of using conventional pressed sheet steel technology.
Fiat’s spaceframe uses welded steel extrusions because of its wide experience in steel body construction. Similarly, Audi uses aluminium extrusions and die castings on the A2 through its development work on the A8. However, where the Fiat Multipla is driven by tooling cost and product flexibility, the Audi A2 is driven by product cost and weight. The aluminium intensive A2 is 40% lighter than it would be if it had a conventional steel structure.

Like other European vehicle manufacturers, Audi is trying to develop the ‘3-litre car’, an initiative of EUCAR in Brussels: i.e. a vehicle that is capable of traveling 100km on three litres of fuel. If reducing product complexity is possible as a consequence of weight saving, then it is of particular relevance to the 3DC programme.

### 3.3 Complexity

Despite the potential implications of vehicle weight saving and reduction in complexity, current spaceframe body design requires more components than its equivalent conventional structure. In the table above, the Multipla floor and side construction uses 35% more individual parts than the Marea. This means that assembly time and labour content per body is likely to increase.

At first glance one might simply assume that vehicle complexity hinders customer order fulfilment due to the increase in process and system requirements across the supply chain. The Production Variety Funnel was devised as a value stream mapping tool by Hines and Rich (1997) and has been used extensively by 3DC in order ‘to understand how the supply chain operates and the accompanying complexity that has to be managed.’

However, little consideration has been given to the number of variants, or different vehicle models, amongst which components are shared. It is suggested by the author that a nominal increase in vehicle complexity can be justified, such as the number of components that make up a spaceframe, providing they can be shared across model ranges and platforms. Fiat for example appears increasingly likely to introduce a common structure policy, using common extruded components based on the steel spaceframe, encompassing the Multipla, Seicento, Panda, Punto, Palio and the new Ecobasic.

### 3.4 Cost

The savings in tooling costs, half that required for conventional production, for both the Multipla and the A2 has been well documented already in this report. What has been more difficult to determine is the cost of the spaceframe body itself. Fiat and Audi were understandably unwilling to release precise figures, but considering that 80% of final assembly on the A2 body is completed manually, the cost of the body is likely to be higher than conventional structures. It would be wrong to assume however, that spaceframes are a reversion to low technology / high labour intensive work practice. This figure for final assembly hides significant developments in metal hydro-forming, joining technology (adhesives, MIG welding and self piercing rivets) and expertise in casting and panel technology.

In a period of European automotive history where over-capacity, flat demand and low profits are at present common-place, the introduction of a low investment, mid-volume means of vehicle production is perhaps a timely and appropriate strategy. The high labour content of spaceframes points towards the requirement for a skilled, flexible workforce capable of moving from task to task. If this flexibility

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were extended to shifts which could be adjusted according to weekly demand, then the additional labour costs could be partially offset and managed more effectively. Marginally higher labour content per vehicle could therefore be assimilated by a new approach based on flexible work practices and building to order.

3.5 Model Changes

Car life cycles are getting shorter and VM’s must respond to this. In monocoque construction model variants are limited to the dimensions of the existing vehicle. This is because the large floor pan pressings (see figure 2, page 7) cannot be altered without incurring massive additional costs. A strategy of sharing common components such as transmission, suspension units and running gear has evolved in order to retain critical vehicle dimensions, using as many of the original steel pressings as possible. Volkswagen has pioneered the platform and modular concepts, described as its ‘platform strategy’, where a salient feature is its application across brands: i.e. VW Golf, Beetle, Bora, Audi A3, Seat Toledo & Skoda Octavia. It defines a platform as a unit that has no impact on the vehicle’s outer skin, that is, the floorplan, chassis and inner wheelhouses. VAG has only 4 platforms for the total VW, Audi, Seat and Skoda range.

Spaceframe construction represents a new strategy because ‘it is not possible to achieve the same results by the simple adaptation of monocoques’. Model changes are easier because the frame is constructed from a common extrusion whose tooling can be used again, despite alterations to model length and width. Whether the frame is welded (Fiat) or joined together with aluminium cast nodes (Audi) compared with the monocoque, the need for repetitive crash testing is significantly reduced on account its structural efficiency.

The floorplan structure of the A2 consists of simple square section aluminium tube and extending this would be relatively simple. Also, re-tooling the floor pressings, some of which are simply flat aluminium sheet would be relatively in-expensive as they do not form part of the integral load bearing structure of the vehicle. All model changes involving new exterior styling require door, wing and roof pressings to be replaced regardless of body construction. Audi partially solve this on the A2 by introducing a totally glazed roof section, thus saving on the cost of steel press tools. The key benefits of spaceframes in terms of model changes, therefore, lie in the ease to which the integral structure of the vehicle can be separated from its outer panels, minimising unnecessary rework and providing infinite model variety at minimal additional cost.

3.6 Economies of scale

‘Automotive plants can currently make 15% more cars than people want to buy’ (Chris Macgowan).

The economies of scale (EOS) issue is critical to spaceframe construction if it is to ever shake off the reputation of being a low / mid volume means of car production. Conventional manufacture traditionally requires production/sales figures of at least 100,000 units per annum in order to begin to make profits. Despite a lower break-even point, annual production levels for the Multipla and A2 are estimated at around 40,000 to 50,000 cars.

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17 Discussion with Mr Lorenzo Rosti, Senior Engineer Fiat Auto, Turin.

However, most of the European car industry is currently selling more and earning less, cutting prices rather than reducing production. In light of the current over-capacity in Europe, adopting the spaceframe approach, with lower volumes and break-even threshold would seem to be the smart move by VM’s. But if spaceframes are to truly realise their potential in the long term, they must be capable of increasing annual production levels to around 100,000 cars.

The graph below shows the three methods of body construction according to their proposed current area of profitability. They are positioned approximately by cost per vehicle, overall profit and number of vehicles produced per year. The largest area represents Monocoque, in the 100,000 vehicle region, as the predominant means of body construction today and thus attracting the greatest profit. Spaceframe is represented as a smaller shaded area, behind monocoque and corresponding to a point representing around 50,000 vehicles.

Figure 8: Proposed current areas of profitability in automotive body construction.

The graph illustrates the current positions in terms of EOS of composite and spaceframe construction relative to monocoque and the potential (massive) growth required in order to provide a sustainable alternative to high volume monocoque construction. The dotted areas, therefore, represent the growth that composites and spaceframes need to achieve over the next 5 – 10 years. Further research will be undertaken in 2000, examining cellular and line assembly methods in order to ascertain whether emerging assembly methods are capable of meeting the requirements of total customer order fulfilment.

3.7 Assembly

‘.flexibility extends beyond producing different model and variants on one line and dealing with unexpected production bottlenecks.’ (Ken Young, 1998, Warwick Manufacturing Group)

Spaceframes represent a radical departure from the conventional plant layout. The separation of structure from the exterior surface of the vehicle offers a significant opportunity for lean production
and reducing customer order lead-time. The spaceframe extrusions could be supplied and assembled directly on the track. Plastic panels with moulded in colour would not require treatment in a Paint shop and the reliance on Body / Pressings would be significantly reduced. A process of ‘bottom-up build’ (Ken Young, 1999) could be introduced, improving assembly ergonomics for the fitting of large items such as the dashboard and seats.

Many of these concepts will be introduced with Fiat’s Ecobasic small-car, to be launched at the Geneva show this year. The Ecobasic has a steel spaceframe and plastic body, neither of which require treatment in a paint shop. The entire frame, interior, front end modules and exterior panels can be outsourced, making for extremely lean production. Features such as air-con, sat-nav and music systems can be installed as late configuration. The Ecobasic is also Fiat’s first ‘sub-3 litre / 100km’ car.

Figure 9 above shows the potential saving in order lead time if an assembly system based on spaceframe production is compared to a conventional monocoque assembly. By adapting the product variety funnel model (i.e. number of product variants over time) it is estimated that around 12 hours could be saved on current order lead-time.19 The difference between the two assembly processes related to orders is as follows:

**Monocoque assembly**

The process involves a bodys shop, a paint plant and a vehicle assembly line and takes around 20 hours, ignoring the time bodies spend in storage or moving between the various ‘lines’. For basically all sponsor manufacturers, an order is identified with the production at the commencement of the Body

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19 For further info on current order lead-time see ‘The 3DC Paint Shop Survey’ by the author.
shop and remains with a specific vehicle throughout Paint and Vehicle Assembly. The reason for this is that the variety of different bodies is usually high and when multiplied by the range of paint colours means that there are many different painted bodies which are potentially available at the beginning of the vehicle assembly track (as shown diagrammatically as the current product variety funnel). Thus, each painted body has to be built against a specific order from the market place, to ensure the right vehicles are built.

To illustrate this further, bodies can be two-door, four-door or estate, and may cater for sunroofs or even have holes drilled for different requirements. In addition, different markets have different standards for safety and thus the actual panels or struts may be different. Perhaps 100 different bodies may be produced which can be painted in around 13 different colours.

Some manufacturers may not physically attach the order to the vehicles until they are processed on to the Final Assembly line, but this is to overcome problems with the high reject rate in Paint (around 25%). For instance, the first red body of a particular type which is passed as acceptable through Paint will have the first order identified with it, whether it was the first one painted in the Paint shop or not. The fact is that the order was identified for production purposes prior to the Body shop. Thus the lead-time is around 20 hours for an order in conventional monocoque assembly.

**Spaceframe assembly**

With a spaceframe, it is only the frame which is potentially scheduled to the beginning of the track, since the painted panels will be hung on as the vehicle proceeds down the track. Thus, the order does not need to consider Body press / weld or Paint. Figure 9 shows the potential saving in order lead-time of an assembly system based on spaceframe production. It assumes that with the adoption of spaceframes it will be possible to eliminate existing Body and Paint shops. Whilst concepts such as these would until recently have been greeted with scepticism, Fiat has identified similar advantages with the launch of the concept vehicle for the plastic-panelled Ecobasic.

The potential saving of 12 hours represents significant progress in reducing order lead-time. However, spaceframe production also facilitates batch sizes of one; a particular challenge to conventional assembly where batches comprising of identical body attributes are required in order to satisfy line-based process requirements such as welding and painting. Spaceframes break the dependence on a preset assembly sequence where, assisted by the modular frame construction, any combination of model variants could literally be built to order.

Spaceframes, therefore, represent more than a de-coupling of central operations from current production. Merely outsourcing existing bottlenecks such as Paint cannot address current barriers to order fulfilment such as buffer stocks, batches and preset body sequences. It is by realising the implications of integrating body construction with vehicle delivery that VM’s can begin to overcome the existing legacies of conventional production. True flexibility must stem from body construction itself, driven by radical changes to integral vehicle design and assembly.

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21 Vehicle Design is the subject of a 3DC study by the author in the second year of the programme, 2000.
Conclusion

Spaceframe technology potentially offers many benefits: flexibility in design & manufacturing and lightweight construction that reduces fuel consumption and emissions. Tooling costs are halved and manufacturing costs are reduced because model changes can be adapted more easily. The spaceframe allows quicker reaction by VM’s to changing customer demands and offers significant potential in reducing order lead-time.

The majority of spaceframe development has occurred in Europe where competition between composite, aluminium and steel producers is fuelling significant advances in coloured thermoplastic panels and metal hydro-forming. However, spaceframe construction and composite panel technology must find the means of increasing output by two or threefold respectively, before matching the economies of scale of welded steel monocoque.

Whilst there is strong evidence to suggest that over two-thirds of VM’s are actively pursuing spaceframe R & D programmes in Europe, only Fiat and to some extent Audi have committed to extending the concept beyond one model and across a range of vehicles. Although component sharing and platform harmonisation is already well developed amongst VM’s, the modular aspect of extrusions offer significant benefits over existing steel pressing in terms of commonising parts used in vehicle frame construction across product families. Fiat began work in 1991 on replacing its existing platform strategy for Alfa Romeo, Fiat and Lancia and is the most developed of all VM’s in implementing spaceframes. Starting with the Bravo/Brava replacement next year, all future models will be based on a semi-spaceframe structure pioneered by the Multipla.

In separating the structural capability of the vehicle frame from its exterior skin, the spaceframe has broken the longstanding reliance on buffer body stocks, batches and pre-set assembly sequences in conventional automotive manufacture. Reduced order lead-time and batches sizes of one has potentially become achievable by including body construction as a key factor in the delivery process of new vehicles. Significant development is expected in spaceframes and associated technology throughout the new decade.

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