

‘Towards the 3Daycar: Vehicle Design and its impact on Rapid Build-to-order’

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Abstract

This paper identifies the key technological opportunities for rapid build-to-order in vehicle design. It questions the ability of conventional volume car production methods to deliver total customer order fulfillment. It examines the link between body construction, vehicle complexity and capacity as a means of reducing the current average 48 day leadtime, from order placement through manufacture to delivery to the customer. Four case studies of new models at European automotive manufacturing plants suggest that emerging technology offers a significant contribution towards meeting customer demand and shortening order-to-delivery leadtime.

Keywords: *Vehicle design, body construction, complexity, capacity, Build-to-order.*

1 Introduction

The automotive industry is facing one of the greatest challenges since the completion of the first assembly line by Henry Ford in 1913. Despite the introduction of lean production over a decade ago (Womack *et al.*, 1990) poor profitability, excess finished stock, over-capacity (Pemberton 2000) and consolidation have persisted in Europe. However, a new topic is emerging: Build-to-order (BTO) or demand driven production (Shapiro 1992, Womack & Jones 1996, Bicheno 1998, *et al.*). Building to order can radically change the manner in which the industry operates by eliminating stocks of finished vehicles sitting in compounds, eliminating dealer discounting on the forecourt and delighting customers with rapid delivery which arrives exactly according to specification.

This approach seems both compelling and logical, after all: “*why make anything your not surely selling ?*” (Van Hoek 1998). Personal computers, photographic development and spectacles are

all examples of products that have shortened leadtimes in the past decade, offering 'instant gratification' to customers. Vehicle manufacturers (VMs) also recognise the significance of BTO and are implementing changes, such as Renault (Project Nouvelle Distribution), BMW (Customer Orientated Sales Processing), Ford (Order-to-Delivery) and Volkswagen (Customer to customer). However, the average leadtime for European cars, from order input through manufacture to delivery is 48 days. Average stocks of finished vehicles held in distribution centres is around 50 days (Williams 2000). This paper examines vehicle design as a 'technological inhibitor or enabler' to time compression and as a distinct yet compatible approach with other aspects of technological research, such as the management of information systems and vehicle telematics.

The 3DayCar (3DC) programme was established in 1999 to examine the impact of BTO across the total automotive supply chain in the UK. The objective is to deliver a framework in which a vehicle can be ordered, built and delivered to customer specifications in three days. 3DC is a complex project which aims to understand the current practices, relationships and technologies that exist between automotive suppliers, manufacturers, logistics, dealers and customers. It brings together researchers and industrialists from all areas and is driven by six research streams: systems, organization, technology, environment, marketing, and finance.

2 Vehicle design and rapid build-to-order

The automotive industry in Europe faces fierce competition in all its major markets and is dealing with a customer who is less patient and more demanding in terms of vehicle choice (Williams 1998). Whilst vehicle manufacturers develop shorter product lifecycles and offer a greater variety of models, this provides shorter 'market windows' in which to generate the sales volume necessary to support the massive development costs of a new vehicle (Holweg & Greenwood, 2000). The current system of making vehicles represents a 'vicious circle' where forecast based production and push-based selling using discounts and incentives is leading to lower profits, thus more volume is needed to maintain the equilibrium (Holweg & Jones, 2001). BTO may offer a new direction for manufacturers who suffer in this climate of spiraling costs and punctured profits.

This paper identifies the key technological opportunities for BTO in vehicle design. It examines the link between body construction, vehicle complexity and plant capacity. Body construction determines the sequence of processes and fitting of components. Complexity determines the number of components per vehicle and total stock in production. Plant capacity determines the rate of supply of finished vehicles to the market. Whilst the linkages between construction, complexity and capacity are complex, their cumulative effect has a profound impact on vehicle delivery leadtime.

Building to order implies responding to individual customer requests, not simply producing large numbers of vehicle for stock and encouraging their sale by promotion and discounting. Batchelor argues that “*regardless of how lean a vehicle has been produced, a vehicle without a buyer is waste of the worst kind*” (2000). BTO, therefore, offers significant benefits to both producer and customer. The costs associated with excess stock and discounting to encourage sales of unpopular models is eliminated, and customers can choose their exact specification and receive a commitment to a delivery date. Whilst 3 days is considered to be the ultimate goal, 5, 10 or 15 days on all customer orders represents a considerable improvement on the current state. This fits with lean thinking philosophy: specifying value from the point of view of the customer, identifying the value stream and making it flow according to customer demand. (Womack & Jones 1996. Hines *et al.*, 2000).

A central pillar in lean production is the elimination of wasteful practices such as ‘batch and queue’ and adopting ‘batch-sizes-of-one’ (Womack & Jones 1996). Traditionally, vehicles have been designed for assembly lines which are forecast driven, producing a fixed sequence of vehicle types, their focus being to minimize costs rather than to cater for the flexibility of customer demand. In order to ensure this fixed mix, the paint shop has to produce painted bodies in a reliable manner or to hold ‘body buffers’ as work-in-progress inventory (Fujimoto 1997). An unreliable production and delivery process encourages dealers to sell from stock, rather than place orders on the factory and perpetuates the stock push system. Furthermore, customers do not know whether the car they receive is factory fresh or has been in stock for months. It is believed that each customer order must become a batch-size-of-one, meeting exact customer requirements in terms of specification and delivery date. A change in mindset is required to shift towards BTO, suggesting dramatic rises in flexibility and responsiveness across supply chain partners. In production this is traditionally achieved in two ways: either through increasing labour levels and investing in equipment, or by developing new design solutions, such as adopting modular assembly.

Whilst this paper focuses on vehicle design and innovation, it attempts to avoid the trap of technology euphoria. Hines *et al.*, (2000) caution against directing attention only at specific areas in the value stream. They cite the example of just-in-time (JIT) delivery in the automotive components sector where:

“...success is measured in reducing inventory or leadtime by a further few minutes or hours [...] a more holistic vision of the industry would show that in many cases there are weeks or even months of finished product downstream of the car assemblers.” (p5)

Vehicle design is examined here in the context of its impact on the total supply chain or ‘big picture’ and is not limited to the design process. Minor improvements to the product architecture may have far reaching, dramatic effects across the total supply chain (Clark & Henderson 1990). Rapid BTO implies that consumption of time, like cost, is quantifiable and therefore manageable. Stalk & Hout argue that today’s new generation companies recognize time as the fourth dimension of competitiveness and place extraordinary emphasis on R&D and innovation (1990). This paper focuses on BTO as a core principle of vehicle design in the 21st century and considers its basic elements: body construction, complexity and capacity.

Body construction

The welded steel monocoque has provided the platform for the development of volume car production through out the 20th century. Whilst Henry Ford is credited with the mass production of the automobile, combining assembly line technology with the scientific labour schemes of Frederick Taylor, it is Edward Budd who advanced body construction technology from cast iron and wooden panels to pressed steel, converting an Edwardian assembly model into modern mass production. High levels of economies of scale were achieved from the standardization of parts and the high volume production of common pressings. This all-steel body, or “*Buddist paradigm*”, abandoned the separate body & chassis design of earlier models and developed the unibody or monocoque body structure, becoming the single most important factor in the economics of vehicle construction and which is still applied to this day (Wells & Nieuwenhuis 1997, 2000).

Developing a BTO environment in 21st century production using the conventional steel monocoque body presents a significant challenge. The principle of the monocoque is based on a ‘structural skin’. Outer body panels are combined as part of the overall load bearing entity of the vehicle, which then requires all operations to be performed on-line and in a fixed operational sequence: *press - weld - paint - final assembly*. This method of body construction, synonymous with large batch sizes and painted body buffers, limits responsiveness and the ability to build-to-order (Howard & Miemczyk 2000). Despite the predominance of the conventional steel monocoque body, there is growing interest by volume manufacturers in alternative methods of construction, shown in table 1. Spaceframe construction is significant to BTO, because the structural frame and non load-bearing panel design can ‘de-couple’ production (Hoeskstra & Romme 1992). Customer orders can be attached later in production to a generic frame that is customized in final assembly. Wasteful, environmentally unfriendly processes such as vehicle painting can be removed from the assembly line almost entirely, where panels can be outsourced to suppliers or molded as coloured thermoplastic panels. Alternative vehicle construction can

enable BTO by the late configuration of finished exterior panels at final assembly or even at the dealer service centre.

Table 1 Alternative body construction worldwide, 1980 – 2000				
Description	Body type	Design / production status		
		Design concept	Production prototype	Launch
Europe				
DC MERCEDES S Class	Spaceframe	•		2005
DC Smart	St. Semi-spfrme TP	•	•	1998
FIAT Bravo / Brava	St. Spaceframe	•	•	2002
FIAT Ecobasic	St. Spaceframe TP	2000		
FIAT Multipla	St Semi-spaceframe	•	•	1998
FORD Th!nk	St. Spaceframe	•	•	2002
OPEL Speedster VX 220	Al. Spaceframe	•	•	2000
OPEL 'Astra' / G90	Spaceframe	•		2005
PROTON Lotus Elise	Al. Spaceframe CP	•	•	2000
RENAULT Espace	St Semi-spaceframe	•	•	1984
RENAULT Spider	Al. Spaceframe	•	•	1995
RENAULT Avantime	St. Spaceframe	•	•	2000
VOLVO	-	•		-
VW AUDI A8	Al Semi-spaceframe	•	•	1994
VW AUDI A2	Al. Spaceframe	•	•	1999
North America				
DC Plymouth Prowler	St. Spaceframe	•	•	1997
GM Saturn EV-1	St. Spaceframe TP	•	•	1996
GM Saturn L & S series	St. Spaceframe	•	•	1997
GM Saturn SUV	St. Spaceframe TP	•	•	2000
Japan				
NISSAN AL-X	Al. Spaceframe	1996		
HONDA NSX	St Semi-spaceframe	•	•	1995
HONDA Insight	Al. Spaceframe	•	•	1999

KEY: Al: Aluminium St: Steel CP: Composite Panels TP: Thermoplastic Panels

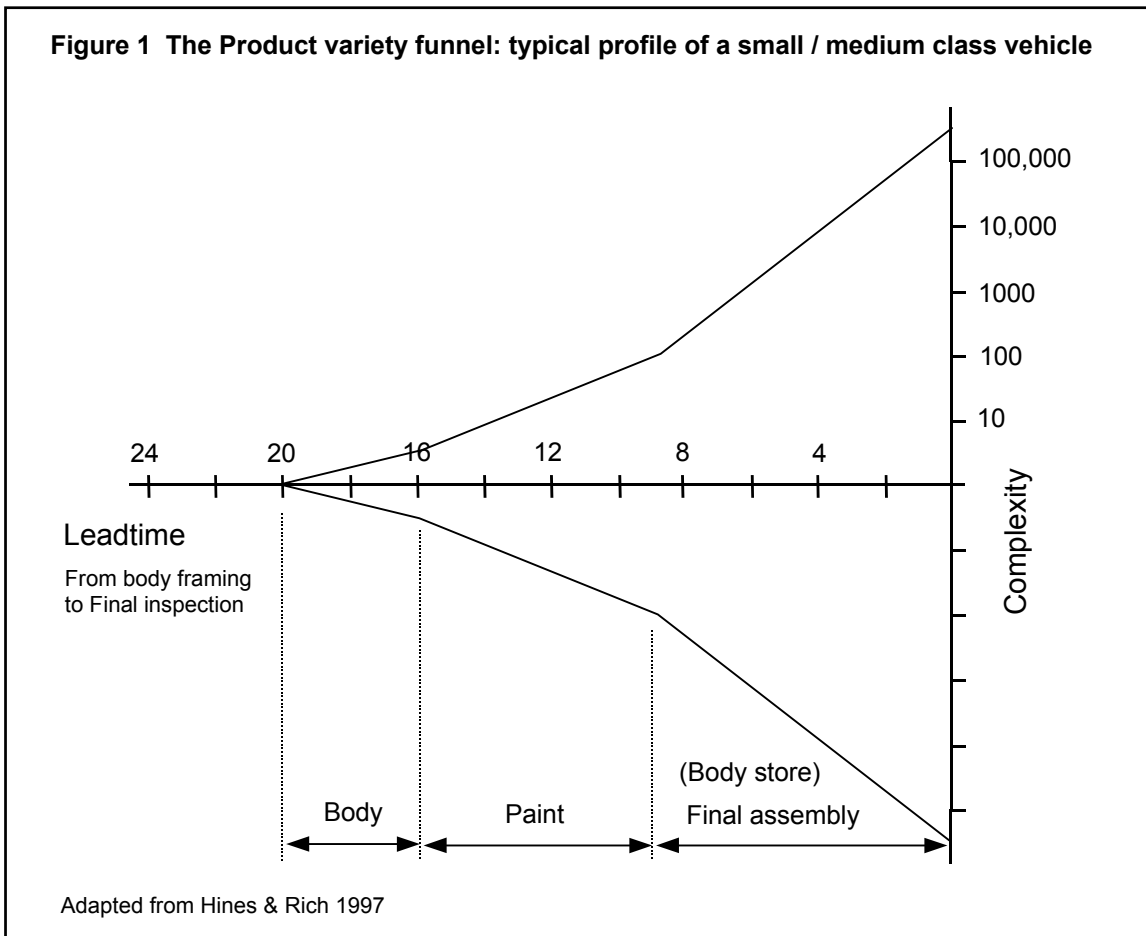
Complexity

It is important to distinguish between vehicle complexity and variety; both of which represent a major inhibitor to rapid BTO. Complexity is defined as the level of internal component variation

handled by manufacturing and logistics operations sufficient to construct the vehicle. Typical automobile complexity today comprises around 4,000 to 5,000 parts (Fine & McDuffie 2000).

Variety

Variety is defined as the level of product choice offered to customers (Batchelor 2000). High levels of variety are normally associated with an increase in parts complexity, leading to a trade-off between the variety offered in the marketplace, the volume of production and the effectiveness of manufacturing operations (Slack *et al.*, 1998). Variety can range from 820 specifications: Nissan Primera, to 3 billion: Mercedes Benz S-class (Holweg & Pil 2001). A dichotomy exists between product variety and inventory, which obstructs just-in-time production with high variety environments (Bennet & Forrester 1993). Two approaches can be used to minimize the impact on production: 1. Process based approaches, such as flexible manufacturing equipment. 2. Product based approaches, which allow for high variety whilst reducing the level of component variation, using product platforms, modular design concepts and component standardization (Sanchez & Mahoney 1996, Batchelor, 2000). Increasing attention is being focused on product design, where it is in the “*nature of the architecture*” that much of a manufacturing systems ability to manage variety resides (Ulrich, 1995).



The prospect of adopting BTO and coping with an increase in customized orders presents a serious dilemma to original equipment manufacturers. Greater understanding is required of how future component assembly and supply may operate and how complexity can be kept at a realistic level. Tools such as the 'Production Variety Funnel' (Hines & Rich 1997) were originally used to compare the complexity and leadtime of internal operations between industries. It is used in this paper to highlight the build-up of parts complexity in vehicle production (figure 1). Holweg and Greenwood (2000) prove that there is no correlation between complexity and variety: this implies that many further opportunities exist to reduce complexity in plants today.

Modularity can be applied to managing complex systems, by breaking them into parameters and tasks that are *interdependent within and independent across* vehicle architecture (Baldwin & Clark 1997). Pine (1993) also argues that mass-customized products can be achieved through component sharing and product modularity. Three types of modularity are of interest in rapid BTO: modularity in design (MID), modularity in production (MIP) and modularity in use (MIU) (Sako & Murray, 1999). Their benefits include, MID: reductions in complexity resulting from reduction in parts, MIP: leaner production due to less operations performed on the line and MIU: higher product variety by offering customers a choice of modules. Minimizing internal vehicle complexity enables BTO by reducing inventories, part count and assembly lead time. The current emphasis on integration of vehicle modules for specific models, conflicts with the popular notion that the automotive industry should increase parts sharing and standardization (Wallbank 2000). However, where styling is not an issue this can often be overcome.

Capacity

In a true BTO environment customer demand may fluctuate on a daily, even hourly basis, requiring a system that is more responsive but not significantly more costly in terms of capital investment or inventory. Conventional capacity management involves long range forecast planning, management of bottlenecks, smoothing of product schedules and balancing stocks of components to optimize out the peaks and troughs of demand. Whilst capacity has been traditionally governed more by production planning and inventory management than by the configuration of product architecture, current measures such as batch size, inventory and lead-time may be improved by applying principles such as Design for Assembly (Boothroyd & Dewhurst 1987) and Design for Manufacture (Ettlie 1987).

Pemberton (2000) defines full capacity as if the product is in sufficient demand to allow continuous operation of production lines, or if it "*constantly achieves 90% of installed and manned capacity*". In 1995, the European Commission (EC) calculated the average utilization in the European automotive industry of 71%, a figure which "*will not improve significantly up to*

2000.” The EC argues that capacity is defined by the particular section of the plant which is considered to be the greatest bottleneck. Similarly, Goldratt (1990) suggests that it is bottlenecks that should govern both throughput and inventory, in order to maintain a continuous flow of materials through the plant. In theory, by eliminating bottlenecks in the system it is possible to maximize efficiency and improve order delivery to the customer. However, Maples (1993) argues that despite the objectives of most manufacturing systems to operate as close to full manufacturing capacity utilization as possible, there are several disadvantages in doing so. Retaining excess capacity is essential, if fast reaction to change and flexibility are important competitive requirements.

Whilst consensus over capacity remains divided, the termination of vehicle production at Dagenham and severe cut-backs at Luton, ensure it remains high priority on business and political agendas. ‘Maximizing capacity’ in the automotive sector typically signals a productivity-driven response. Traditionally this involves: either increasing plant labour levels, adjusting line speed and adding extra shifts, or closing down older less efficient factories. The emergence of concepts such as BTO, customer-pull and responsiveness matches the increase in specialist vehicles and niche markets, represented by the sports utility sector. Is it possible that the start of the new century coincides with a genuine shift in thinking, away from production-push and economy of scale, towards customer-pull and economies of scope? In Europe, the emergence of innovative metal-forming techniques and materials is a key factor in platform sharing, spreading the cost of investment across many models. Also, the delivery of modules by 1st tier suppliers located in adjacent parks can reduce complexity and leadtime in production. The scope of vehicle design appears to be increasing, therefore, including not only *product characteristics* but also the means for its *delivery*.

3 Methods

The research design is based on a case study of the production of four small / medium passenger vehicles, manufactured in plants across Europe by some of the world’s largest and leading VMs. The case study is an empirical inquiry that both investigates contemporary phenomenon within its real life context and copes with a technically distinctive situation in which there will be many more variables of interest than data points. As a result it relies on multiple sources of evidence, with data needing to converge in a triangulating fashion and benefiting from the prior development of propositions to guide data collection and analysis (Yin, 1994).

The multi-methodological nature of vehicle design and production is reflected in the study where a number of phenomenological and positivistic methods are used. A series of semi-structured interviews were conducted with senior managers in production engineering and design, followed

by a private tour of the manufacturing facility. In some cases, permission to visit was granted only after an assurance was given that the identity of the manufacturer would not be revealed in subsequent literature. A questionnaire was developed specifically to examine the paint shop in terms of colour batch size, rework, buffer levels and environmental emissions. This was considered an important aspect of the study as the car body painting process is a “*notorious place for rework*” (Fujimoto 1997) but often an area that is difficult to gain access to due to its hazardous nature and the limited time available during normal site tours. The overall results of the survey were fed back via internal reports and sponsor conferences. Summaries of the key findings from the four manufacturers are presented in table 2.

4 Findings

	Manufacturer / model	A	B	C	D
	Model class / seg.	B	B/C	B/C	A
Construction	Body construction	Welded steel monocoque	Steel semi-Spaceframe	Aluminium Spaceframe	Pressed steel / plastic panels
	Body tooling cost (£)	63,000,000	60,000,000	80,000,000*	20,000,000 (+ mould tools)
	Facility investment (£)	196,000,000**	50,000,000*	109,000,000	685,000,000
	Body weight: (kg)	200	232	130	158
	Total vehicle:	1000	1300	895	720
	Body assembly automation (%)	85%	20%	85%	95%
	Body assembly leadtime (hours)	7.5	12.5	7.5	2
	Method of fixing exterior panels to body	Robotic spot weld	Manual spot weld	MIG seam welding and steel rivets	Plastic clips
Capacity	Total capacity (units / pa)	250,000	60,000	75,000	200,000
	Production in 2000 at plant visited (units / pa)	115,800	46,105	25,238	104,681
Complexity	Body-in-white complexity:	8	2	2	2
	Large pressings	52	29	20	30
	Small pressings	100	60	35	50
	Folded sheet	-	20	-	-
	Brackets	60	-	-	26
	Castings	-	-	18	-
	Extrusions	-	-	28	-
	Total:	212	109	101	106 (+ panels)
Painted body colours	14	13	8	2	
Total variety	150,000	20,000	50,000	15,000	

* Estimated figure

**Replacement model

Vehicle manufacturer A

Vehicle manufacturer A represents the most conventional approach to volume manufacture. The welded steel monocoque body indicates the capability for high volume production, but is currently running at only 46% capacity. The conventional line layout is highly automated, using robotic spot welding as the principle means of assembling the pressed steel body parts together. 8 Body-in-white variations are built: 3-door, 5-door, estate and van (left and right-hand drive). This model represents the most complex in terms of body construction and variety, and will be replaced next year.

Vehicle manufacturer B

Vehicle manufacturer B decided to experiment with the principle of the steel spaceframe in the late 90s and converted some of its existing facilities to support the project. The assembly line layout is relatively low cost where almost all BIW operations are manual and use no robots. The line feeds into a conventional paint shop that is shared with two other conventional models. Its body is constructed from beams, simple profiles, simple pressings and complex pressings. Whilst not a true spaceframe (all panels are structural) the relative simplicity of the design of the frame is reflected in the significantly lower number of parts, a feature of all the alternative body structures. A future strategy is to have BIW parts sharing between models and within model derivatives.

Vehicle manufacturer C

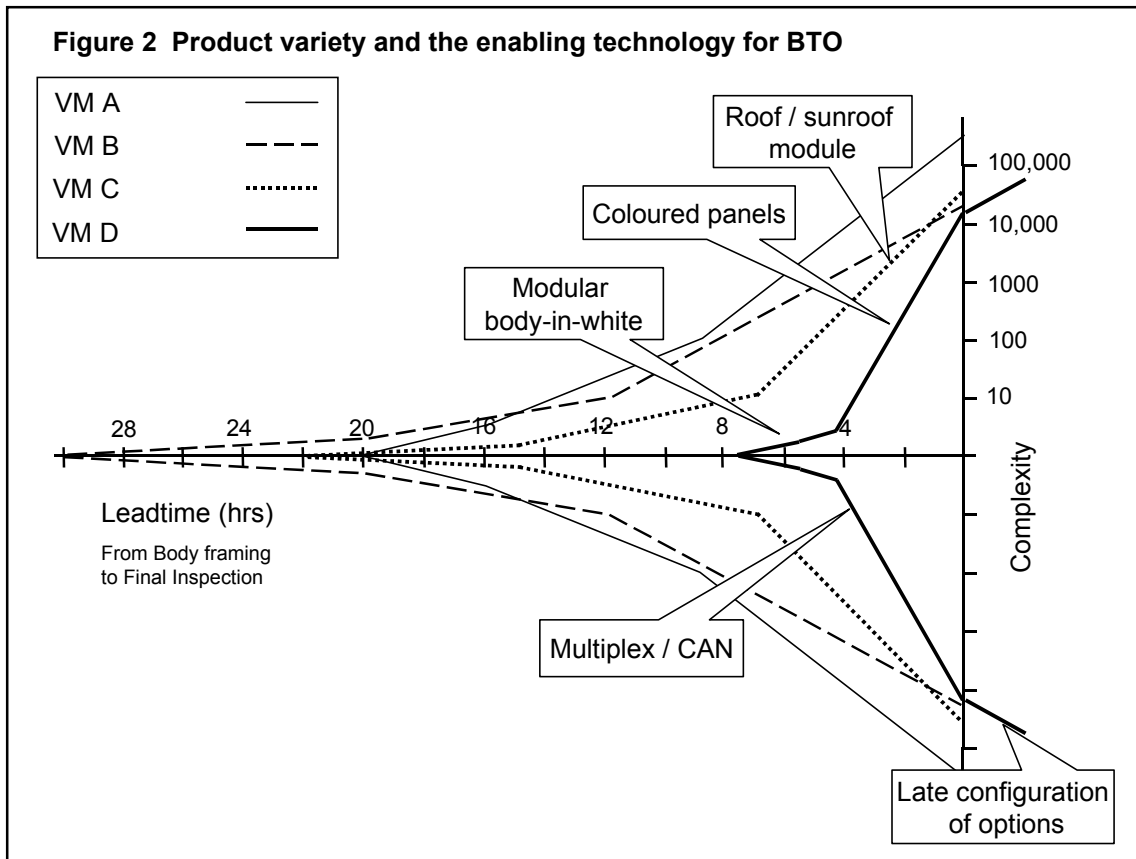
Vehicle manufacturer C has used its knowledge of working with aluminium to develop a structure that is close to a true spaceframe. Whilst 80% of the load is taken by the frame, exterior panels do contribute to the rigidity and stability of the structure. The plant is housed in a 2-storey site, with 5 main areas: platform, framing station, left & right panel station, roof and final assembly. The high tooling and facility investment is reflected in the number of innovative processes used and high level of automation: 200 robots are deployed around the site. MIG welding and self-piercing steel rivets are used to assemble the frame, which is accurate to within 0.2mm. A and B-pillars are vacuum pressure aluminium die cast, capable of a minimum wall thickness of 1.8mm. The single-B pillar casting replaces 6 parts used on an earlier model and the longitudinal roof bar is a hydro-formed extrusion, both are regarded as highly innovative solutions. A Controller Area Network (CAN) wiring system replaces the traditional 'harness' found in most other vehicles and eliminates the need for hundreds of individually configured wiring systems needed to operate the wide variety of in-car option combinations. The sunroof is fitted as a complete glazed section during final assembly and whilst this requires a modified body, this is not far from the 'roof module' concept that can eliminate the sunroof complexity issue. This is a significant factor because it occurs at BIW, the earliest stage of production.

Vehicle manufacturer D

Vehicle manufacturer D founded its project in the mid 90s on a greenfield site, where the vehicle design and plant layout were considered as a total concept. The plant is shaped as a ‘cross’ with 1st tier suppliers positioned according to their order of assembly on the production line. Core system partners add 90% of the vehicle’s value: Body, panels, cockpit, doors, tailgate, powertrain and front module. It is possible to mistake the pressed steel body as a monocoque, however, attached to the outside of the body are colour injection-moulded plastic panels. This radical ‘Independent Body and Panels’ (IBP) concept minimizes the impact of the paint plant in production, which is only required to provide a protective coating for the body. Decorative water based finishes are provided in addition to the four core panel colours. Panels can be easily changed or ‘late configured’ at dealer centres. Total production leadtime is 8 hours, compared with the 3Daycar Survey average of 20 hours (Howard, 2000). There is some discrepancy, however, between the plant belief of a high BTO content (95%) and the dealer claiming to put in 75% as stock orders for late configuration.

5 Discussion

This paper brings together some of what is perceived as the common principles and key technologies for rapid BTO. Whilst it is acknowledged that not all of the case studies bear an



exact comparison due to some differences in model class and age, it is possible to generalize and develop useful observations. Figure 2 reproduces the product variety funnel overlaid with examples of enabling technology that minimize complexity and leadtime. It shows that developing BTO requires ‘*changing the shape of production*’ by adopting a radical new approach driven or enabled by vehicle design. Figure 2 shows that the product variety profile of model D is very different from that of other manufacturer’s models. Reducing product complexity and production leadtime is an essential element of the change process, shown here by the ‘shorter, flatter’ profile. Model D embodies many of the key technological enablers, such as modular BIW construction, thermoplastic body panels, roof modules and the late configuration of options. These are included below in table 3 as the key BTO requirements, vehicle design technology and capability.

Requirement	Technology / capability
Construction	
Develop body appropriate to configuration requirements	Steel or aluminum spaceframe 'Independent body and panels'
De-couple paint	Colour thermoplastic panels (Painted body storage tower)
Complexity	
Minimise complexity in design & production	Modular body-in-white construction 'Multiplex' / Controller Area Network Roof, door, front/rear end modules Late configuration
Capacity	
Increase volume flexibility	Modular body construction Platform / parts sharing (Production Optimization software)

On what basis in the future will VMs adopt a responsive manufacturing strategy: production / process-based or innovative design and new technology? Whilst these are not mutually exclusive, we suggest that alternative body construction and innovative vehicle engineering in partnership with key suppliers is emerging as an increasingly popular approach. Examples of technologies that are not specifically design related include Painted body storage towers and Optimization software. Painted body storage towers are considered a short-term enabler to BTO, allowing

unreliable upstream processes to be de-coupled and enabling the customer order to be attached after Paint. Production Optimization software provides real-time capacity planning, based on plant-specific constraints. But neither Body storage towers nor Optimisation software can ultimately be considered a substitute for implementing best practice across the total production process. It is vehicle design that offers the most significant and long-term potential for transforming the industry.

Some manufacturers in the study described their development of new body structures as an experiment. This is surprising, particularly when the very high level of investment seems to be at odds with the relatively low annual production volumes in most cases. Other factors may be at work here in addition to the drive to streamline production and minimize delivery leadtime, such as the need to develop lightweight, fuel-efficient vehicles for the future. A significant hurdle facing all manufacturers is generating a suitable return in the notoriously competitive small car market. The principle of BTO may seem sound in theory, but in reality the cost of converting existing production sites or borrowing sufficient capital for new projects may stretch the rules of amortization too far for some manufacturers. It is ironic that perhaps only the biggest will be able to fund the smaller, more flexible plants of the future.

6 Conclusion

Our objective has been to identify the key technological opportunities for BTO in vehicle design. We have shown that by considering the vehicle as a 'product architecture', characteristics such as body construction and vehicle complexity can affect total delivery leadtime, not just in production. This reinforces and broadens the significance of vehicle design, now included as part of the bigger picture or seen as part of 'the whole' in terms of the order fulfillment process. Design engineers who think their boundaries begin and end at production must reconsider, because vehicle construction and the links with complexity and process reliability have a wide-reaching impact that stretches across the delivery process. In the future, effective screening, management and integration of new technologies by VMs and their partners is essential in order to maximize the potential for rapid BTO.

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