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More sustainable automotive production through understanding decoupling points in leagile manufacturing

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ABSTRACT

Attempts to link 'lean' and 'green' have a long history, yet they mostly remain wedded to an eco-efficiency agenda. The question addressed here is to what extent lean can inform more radical change towards greater sustainability in industrial systems. The automobile is one of our least sustainable systems and the main issue is overproduction. Yet, the current automotive business and manufacturing models depend on high levels of production due to the need for economies of scale determined by the chosen production technologies. These technologies center on the internal combustion engine and the all-steel body. This paper shows through a review of the 'leagile' literature, that a new understanding of the factors that determine the 'decoupling point' between lean and agile processes can be used in order to bring about a radical shift in economies of scale in car production such that lower volume production becomes feasible thereby reducing the need for overproduction and enabling a move towards more sustainable car production and hence consumption. A case study of the Morgan Motor Company is included to illustrate how such an approach could work in practice.

1. Introduction

There have been several attempts over the past twenty years or so to link, or even fuse the concepts of 'lean' and 'green'. Although early pioneers of lean production and subsequent 'lean thinking' (Womack et al., 1990; Womack and Jones, 1996) on the whole failed to make this connection, some, including Romm (1994), immediately saw the potential to combine the 'lean' with the 'green', or 'clean' as Romm put it, while others instead highlighted the potential negative environmental impacts of some 'lean' practices such as Just-In-Time (JIT) (Nieuwenhuis, 1994). The following twenty years saw a series of studies attempting to integrate the two concepts, exemplified most recently by works like Dües et al. (2013) and Wong and Wong (2014). A particularly useful contribution is the recent literature analysis surrounding these themes by Martinez-Jurado and Moyano-Fuentes (2014), who also identify automotive as the most studied sector in this context, possibly reflecting the fact that lean thinking originated in the automotive sector, although it could also be argued that nowhere is this fusing of lean and green more relevant than in the case of the automobile.

In the automotive sector, both products and processes have been the subject of considerable efforts to reduce their impact, yet it is also clear that annual worldwide production and sales of some 70–80 million vehicles is not environmentally sustainable as presently understood, however environmentally optimised both products and production may have become. In fact, the automobile is probably one of the least sustainable of human systems. Yet it has also become tightly interwoven with modern societies and economies, making it particularly challenging to entice towards greater sustainability. Progress made so far in product terms has focused primarily on emissions and fuel consumption and should be categorised as 'eco-efficiency' measures rather than moves towards genuine sustainability, while, similarly, in production terms the focus has been on the reduction of paint-shop emissions, energy efficiency measures and reduction of waste. The problems are wide-ranging, but the most obvious is this sheer annual production volume, amounting to some 63 million cars and light trucks in 2012 alone (OICA, 2014). Having adopted mass production, it has become near impossible to produce cars at low volume, thereby creating significant barriers to change (Wells and Nieuwenhuis, 2012). However, these barriers within the mass production system are not insurmountable.

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The present study attempts to progress the discussion of how to link lean and green and extend it towards a sustainable production approach by incorporating not only recent advances in lean thinking, particularly its embracing of 'agility' as a concept, but also the recognition of the limitations inherent in an eco-efficiency approach. In the process, an attempt will be made to summarise developments in lean and agile thinking and then extend this to apply it to a model of potentially more sustainable production of automobiles at lower volumes. A case study of the Morgan Motor Co. is included as an illustration, although this is used merely to explore how the principles of 'leagile', and in particular how the core concept of the 'decoupling point' could be used to inform a more sustainable, lower volume and hence lower environmental impact system that can nevertheless deliver personal mobility as it has come to be understood.

1.1. Background

The need to reduce new car production volumes will come into even starker focus in the coming years as a result of technological developments, as a consequence of which the ratio of embedded carbon to in-use carbon emissions will change dramatically. This will make the environmental argument for making fewer, more durable cars even more compelling than it is today. The notion of product durability has long been on the margins of environmental concern (OECD-MIT, 1994; UN, 1997; Cooper, 2005), although some durability work has focused specifically on the car (Porsche, 1976; Stahel and Reday-Mulvey, 1981; Nieuwenhuis, 1994b, 2008; de Groot and McCrossan Maire, 1998). The issue of a car's life expectancy has come to the fore again due to work on embedded (or 'embodied') carbon in cars, notably that by Ricardo on behalf of the UK Carbon Trust (Ricardo/Carbon Trust, 2011) and also the work by Hawkins et al. (2012). It is clear from these contributions that as we move towards greater electrification of the automotive powertrain from hybrid, through plug-in hybrid, to battery electric vehicle (EV), and possibly fuel cells, the proportion of embedded carbon increases in relation to carbon emissions in the use phase from the current typical ratio of 20:80 (embedded: use), to a possible future ratio of 60:40. Embedded carbon in the case of a car includes the mining of raw materials, their transport, production of semi-finished products, of components, as well as the production of the car itself.

The Ricardo study shows that the body contains the largest proportion of embedded carbon (30%), followed by the engine (20%), which, by optimising existing technologies, could be reduced by around 50%. However, there is also an increasingly strong case to be made for extending the useful life of the car itself. The analysis by Hawkins et al. (2012) focuses specifically on the difference between what they term 'conventional' and electric vehicles. They calculate that the global warming potential benefit of EVs as a result of this amounts to 10–24% with the average European electricity generating mix, assuming a lifespan of 150,000 km. Increasing the lifespan to 200,000 km increases this benefit to 27–29% relative to petrol cars and 17–20% relative to diesel. However, decreasing the lifespan to 100,000 km reduces the benefit to 9–14% against petrol, and no discernable difference with diesel. They suggest, therefore, reducing the impact along the supply chain while also reducing in-use emissions through lower carbon energy generation. Neither study advocates a longer lifespan, but this would seem a more logical conclusion. EVs already are likely to last longer than IC engined vehicles. This is based on historical experience with older EVs, as well as more recent experience in countries like Norway and some specific commercial fleets, which have shown them to be very reliable and long-lived (Nieuwenhuis, 2014). However, will consumers be able to adjust to keeping cars for longer, and will the car industry be able to handle such a transition towards making fewer longer-lasting cars? The answer to the latter may well lie in some of the strategies outlined in this analysis.

2. Lean and green

Martinez-Jurado and Moyano-Fuentes (2014) provide a useful summary of works attempting to link the lean with the green and they distil a number of themes from their analysis. They explain that while initially the focus was on greening single sites or firms, later arguments in favour of greening supply chains come to the fore (e.g. Mason et al., 2008). They show that in recent years most of the focus in the literature has been on the impact of lean practices on environmental sustainability, which they define as meeting the needs of current stakeholders without compromising those of future stakeholders – possibly a rather narrow definition, which depends crucially on how 'stakeholders' are defined in a particular context. They identify some recent contributions, notably Vinodh et al. (2011) and Aguado et al. (2013) that begin to link lean management and green manufacturing, which, combined with works adapting lean concepts to environmental concerns along the supply chain as a whole, such as Mason et al. (2008) have moved the debate forward towards a more integrated approach. However, they also highlight problems with this approach, notably the concept of *heijunka* or production levelling, which highlights the tension between the needs of the production system with those of the market (Naylor et al., 1999; Mason-Jones et al., 2000) that forms the basis for the discussion here.

On the whole, as outlined by Martinez-Jurado and Moyano-Fuentes (2014), the approach taken by such studies can best be categorised as 'eco-efficiency', whereby the 'lean' priority of removing 'muda' or waste in the broadest sense from any process, can easily be extended to apply equally to the wasteful use of natural resources, whereby a 'green' approach prioritises the reduction or removal of such waste; a very similar concern. An eco-efficiency approach is predicated on the assumption that there is nothing inherently wrong with the product or process under consideration, but that carrying it out in a less wasteful manner is itself environmentally beneficial. To some extent this may be a valid assumption; however, we are also then often dealing with 'low hanging fruit' in terms of wider environmental benefits; further, more fundamental change is inevitably needed in due course.

Such eco-efficiency benefits are then extended to the business side whereby the 'double bottom line' at least can be hit: eco-efficiency is thus easily combined with business efficiency: saving costs. Walker and Salt (2006) warn against over-use of efficiency as it is often understood, arguing that instead, natural systems favour a degree of 'redundancy' in order to achieve 'resilience' and therefore often appear to us as inefficient. Within a wider sustainability context, therefore, many of such eco-efficiency initiatives provide at best partial results. For example, where a process or product is inherently unsustainable, it is still offered, only with a reduced environmental impact. Instead, an attempt is made here to revisit the lean concept, combined as it has become in the more recent literature with the notion of 'agility' to create a creative fusion now known as 'leagile', and to assess to what extent this concept can then be used beyond the context of an eco-efficiency brief in order to make a serious contribution to a genuine sustainable production and consumption agenda – although the emphasis here will be on the former: production.

3. Lean and agile

With the introduction of lean production, originally as the Toyota Production system, mass production became more efficient

– more could be done with less; less in terms of resources, therefore suggesting a move towards greater environmental efficiency also. This prompted works such as Romm (1994). The lean concept gradually moved through the automotive industry, popularised primarily by Womack et al. (1990). However, it soon became clear that with lean production a degree of flexibility was lost and moves towards greater 'agility' were introduced only to settle at a kind of compromise solution now termed 'leagile'. The present study argues that not only does this approach lead to greater conventional effectiveness in mass production systems but, more importantly, it also opens the door towards reducing the volumes of cars produced, while at the same time retaining a viable automotive industry. The key, it is argued here, to achieving this is a new understanding of the impediments to the location of what has been termed the 'decoupling point' between the lean and agile phases of the value chain. To illustrate how such an approach could be used for viable lower volume automotive production systems, an existing low volume firm, the Morgan Motor Company, is used as a case study. It is shown that a judicious mixture of lean and agile activities along its extended value chain allow this low volume operation to survive and thrive within the existing mass production-dominated system.

The concept of lean production has been challenged by those seeking to accommodate a greater degree of flexibility, or agility in supply chains. Essentially, while lean was regarded as the answer for all supply chains at one stage (Womack et al., 1990), it was found that tensions could arise where some supply chains interface with markets – akin to Walker and Salt's (2006) efficiency vs resilience argument in natural systems. An overview of these developments in approaching the concept of 'lean' was provided by Moyano-Fuentes and Sacristán-Díaz (2012). In view of some of the limitations of lean, it was concluded that for certain supply chains supplying certain markets, a more agile approach was required, which at times could undermine to some extent the leanness of the supply chain. The crucial question became how lean and agile elements could be combined within a single supply chain and at what point in that supply chain the change from lean to agile should be made – this became known as the 'decoupling point'. Over time, two types of decoupling point came to be primarily identified: the material decoupling point and the information decoupling point.

In the present study, this discussion is linked with a case study analysis of the rarely studied specialist sports car sector, which has used precisely these principles in order to ensure its survival and may provide pointers for a potential trajectory towards more sustainable lower volume production of more durable cars. This fact is not well understood, as the debate – particularly in an automotive sector context – has been dominated by models of mass production (cf. Moyano-Fuentes et al., 2012 for a recent example). This is understandable, as Toyota provided the original model for the lean paradigm. However, it is found here that by moving the material decoupling point further up the value chain than is customary in mass car production, beyond the boundaries of the firm in fact, the low volume specialist car industry has dramatically reduced its minimum economies of scale, thereby making this sector viable at a scale far below the production volumes at which conventional mass car producers would be viable. The weakness of the existing 'leagile' literature is that it provides little detail as to what elements determine the location of the material decoupling point. The core argument here is the suggestion that high capital investment processes in the value chain provide barriers to the free movement of the material decoupling point, but that these can also provide a focus for where the decoupling point can most profitably be located. Empirical evidence is provided by a case study of the Morgan Motor Company.

3.1. Integrating lean and agile

Christopher and Towill (2001) conceived three ways in which the lean paradigm and agile paradigm can be integrated to create an effective supply chain. Christopher and Towill (2002) argued that there are three practical combinations, namely: within the same space but at a different time; in a different space but at the same time and a in different space and a different time in the supply chain. These were defined as: the separation of 'base' and 'surge' demand, the Pareto curve approach and the decoupling point approach. Christopher and Towill (2001) also suggested appropriate conditions for each of these hybrid strategies and claimed that these three combinations are complementary rather than mutually exclusive. The rationale behind these three approaches was further explored by Stratton and Warburton (2003). They claimed that where there is a trade-off within the organisation, separation principles can be applied for mitigating the impact of any conflict.

Most pertinent in the present context is the material decoupling point. This approach refers to marrying the lean and agile paradigms by creating a decoupling point in the materials flow. Upstream from the decoupling point, processes are operated on lean principles; inventory is held in generic form and the final configuration is only performed when the customer order is received. Only downstream from the decoupling point is the agile principle applied. Christopher and Towill (2001) stated that this approach can be applied when there is a possibility of modular design in product architecture. In a low volume automotive context, for example, generic components such as powertrain, extrusions for frame construction, etc. could be made by large facilities in order to achieve the desired economies of scale via lean processes. These could then be supplied to smaller assembly facilities that combine these modules and can operate on very low capital investment levels in order to allow maximum flexibility and agility in their interface with the market. This is in reality similar to how Ford built the Model T (Ford & Crowther, 1924).

The 'decoupling point' was introduced by Hoekstra and Romme (1992), and defined as 'the point in the product axis to which the customer's order penetrates'. Later, Mason-Jones and Towill (1999) added that there are at least two pipelines within the supply chain, material flow and information flow and both flows have their own separate decoupling points. Therefore, they introduced the concept of 'material decoupling point' and 'information decoupling point'. This 'material decoupling point' resonates with the 'decoupling point' proposed by Hoekstra and Romme (1992). Mason-Jones and Towill (1999) defined the 'information decoupling point' as 'the point in the information pipeline to which the marketplace order data penetrates without modification'.

Hoekstra and Romme (1992) give examples of simplified supply chain structures with various positions of material decoupling point, ranging from 'buy to order' at one extreme with a decoupling point well up the supply chain at the factory gates of the raw material supplier, via 'make to order' with the decoupling point just before the manufacturer/assembler, 'assemble to order' where that point is at the manufacturing/assembly plant, via 'make to stock' with the decoupling point between assembler and retailer, and 'ship to stock, with that point at the retailer. The manufacturers/assemblers represent one or several businesses in the supply chain. Naim and Barlow (2003) made efforts to link these structures to different supply chain strategies: 'lean' supply chain, 'agile' supply chain and 'leagile' supply chain. At one end of the spectrum, there are 'make-to-stock/ship-to-stock' approaches, which can offer products with short lead times or simply picked off the shelf. At the other extreme, the 'make-to-order/buy-to-order' approaches carry a low risk of stock obsolescence as the product is configured to actual customer requirements from the start of the value-added processes or the purchase of raw materials. These approaches feature high responsiveness. However, the precondition for adopting these two agile strategies is that customers are willing to accept a longer lead-time. A compromise situation is assemble-to-order, which typifies the leagile supply chain. The aim then is to trade-off the risk of stock obsolescence with the requirement of shorter lead-times.

The material decoupling point is also the point where strategic stock is held to buffer the upstream players from fluctuating customer orders and/or product variety (Childerhouse and Towill, 2000; Naylor et al., 1999). Several factors impact on the position of the material decoupling point. On the one hand, the position of the material decoupling point depends on the longest lead-time the end customer is prepared to tolerate (Naylor et al., 1999; Mason-Jones and Towill, 1999; Childerhouse and Towill, 2000; Mason-Jones et al., 2000); while on the other hand, it depends on the product variety and variability in demand. An increase in product variety and fluctuating volume of demand would force the material decoupling point to move upstream, which makes the supply chain more agile. In contrast, a more stable business environment with lower product variety and stable demand would move the material decoupling point downstream, making the supply chain leaner (Krishnamurthy and Yauch, 2007, p 592).

Naylor et al. (1999) argued that a 'postponement' strategy contributes to moving the material decoupling point closer to the end customer, thereby increasing both the efficiency and responsiveness of the supply chain. Postponement here refers to delayed configuration; the final assembly does not take place until customer orders are received (Christopher and Towill, 2000, 2007). Similarly, Childerhouse and Towill (2000) define postponement as the application of the material decoupling point before the point of product differentiation. The core element behind the postponement strategy is modular design. Feitzinger and Lee (1997) proposed two concepts: 'modular product design' and 'modular process design'. Modular product design refers to dividing the entire product into several sub-modules, and redesigning modules with standardised interfaces so that sub-modules can be easily assembled together, which enables components to be manufactured separately and even in parallel and one component can be shared by different products. Similarly, modular process design refers to breaking down the complete production process into several simple independent sub-processes that can function together as a whole, thus, the production sub-processes can be performed separately or can be re-sequenced. On the same basis, some processes can be performed in-house, while others can be outsourced, with this mix changing over time. Modularity enables a company to assemble standard components in the earlier stages of production and delay assembling the components that differentiate the products. Postponement strategies contribute to leanness as well as to agility. On the one hand, by delaying product differentiation, the supply chain produces standard semi-finished products as long as possible. Product differentiation occurs at the material decoupling point, the generic inventory is regarded as strategic stock and only differentiated processes cause delay. This greatly reduces the lead-time from order placement by customers to product delivery; it increases the responsiveness of the supply chain.

However, little is actually said in the literature about the precise nature of the material decoupling point; it is often, by implication, suggested that greater freedom exists in reconfiguring supply chains than is reflected in reality. It is frequently implied that the supply chain designer has complete freedom in locating decoupling points. To the extent that it can be manipulated for strategic or tactical purposes, what determines the location of the material decoupling point in a supply chain, and what are therefore the constraints faced by supply chain designers and managers in managing this point? It is suggested here that these constraints are often determined by levels of fixed investment in the equipment used at various processing stages along the supply chain. Where such fixed investments are high, lean is best, where they are low, agile works well. However, on the whole, the existing literature remains vague on this point.

In the mass production car industry, the key areas of production focus are the integrated steel body structure and the powertrain (engine and transmission). These major subassemblies represent the highest level of investment both in terms of product development and in capital investment in manufacturing. It is therefore these areas that represent both the key to economies of scale in the car industry, but also the main barriers to greater agility in terms of response to customer requirements (Nieuwenhuis and Wells, 1997, 2003, 2007; Wells and Nieuwenhuis, 2012). It is for this reason that, while customers often have access to a broad range of colour and trim variations, for example, their choice in terms of powertrain and body style is limited, despite the now widespread adoption of platform strategies and attempts at 'mass customization' (Alford et al., 2000; Doran et al., 2007; Brabazon et al., 2010). It is also typically the case in mass car production that both the body and powertrain areas remain within the realm of the final assembler, the Original Equipment Manufacturer (OEM). For these reasons, much of Toyota's innovative work was focussed on the area of body production – press shop, body-in-white, and paint, as these are the least amenable to flexibility (Womack et al., 1990).

However, one way of breaking through this barrier to greater agility may be by moving to a more modular design approach, as suggested in the decoupling point literature (Feitzinger and Lee, 1997), and then moving the decoupling point for these key assemblies further up the supply chain, for example by outsourcing engines, and/or outsourcing body/chassis. Another method may be to move to a different type of technology that allows breakeven at much lower economies of scale, such as by abandoning 'Budd-style' all-steel body construction for a different solution (Nieuwenhuis and Wells, 2003, 2007). It is this combination of approaches, that has enabled the growth and survival of low volume specialist firms such as the Morgan Motor Company, one of the world's oldest surviving car manufacturers. Morgan uses traditional 'pre-Budd' coach-building techniques and has never made the transition to Budd all-steel technology (Nieuwenhuis and Wells, 2003). The firm is very successful and prides itself on never having had to lay off any workers and on having been profitable since 1911. Morgan celebrated its first centenary in 2009 (Morgan and Bowden, 2008).

4. Methodology

In terms of methodology, a qualitative approach was used, specifically a case study. Where the approach here is more novel, is in the use of an engaged scholarship model (Van de Ven, 2007). The researchers have over the past 10 years developed a long-standing relationship with the Morgan Motor Co. involving regular meetings and interactions, such that the methodology used constitutes an 'engaged scholarship' approach (Cheney et al., 2002; Van de Ven and Johnson, 2006; Van de Ven, 2007). In engaged scholarship, '… researchers and practitioners coproduce knowledge that can advance theory and practice in a given domain' (Van de Ven and Johnson, 2006, 803). Van de Ven (2007) and Van de Ven and Johnson (2006) argue that research yields better results, from both a practitioner and academic perspective, if academics and practitioners collaborate throughout the research process. This includes defining the research questions as well as theory building. This process is clearly easier to implement where the firm is relatively small, occupying a single site and where lines of communication are therefore short. The researchers are under no illusion that what has been achieved in this respect in the current study would be easily replicated in a large, multi-national automotive mass producer. However, in this case, the ability on the part of the practitioners to engage in higher level thinking, and on the part of the researchers to understand manual craft-based processes and specialist car markets, helped to build a productive engagement on both sides over a number of years.

From this process emerged two research questions. The practitioners were particularly interested in understanding their own business model such that they could explain it to potential investors; members of the financial community often fail to appreciate the differences between mass production and low volume specialist automotive operations. This in a climate where the demise of the small automotive firm was long expected, a view itself apparently borne out by the absorption of many small players by larger mass producers during the 1990s (Maxton and Wormald, 2004). The researchers, however, were primarily interested in exploring the extent to which the low volume production model was actually feasible as the basis for a future more sustainable automotive business and manufacturing model by studying firms that already employed elements of it. Thus, rather than entering the company to carry out fieldwork on a single occasion, the researchers engaged in an on-going dialogue with the company, with the aim of benefiting both the researchers and the company. After a number of informal visits, the outcome of which was some practical research of direct benefit to the company, an exploratory research visit was carried out in February 2008, followed by more extended research visits in August 2008, May 2011, November 2012 and September 2013. On each occasion, the craftsmen and craftswomen building the cars were engaged in informal interviews during an extended tour of the production facilities during which key processes were recorded and discussed, while more formal interviews were also carried out with senior executives. Topics covered focussed mainly on understanding the supply chain, relationships with suppliers and also with customers. Morgan is an SME, employing between 180 and 200 people (the numbers varied during the different research visits, increasing to just under 200 by the time of the final visit due to the addition of capacity to build the new three-wheeler). It is therefore possible to engage with a significant proportion of the workforce during such visits, thereby exploring different aspects of the operation. Between visits, more detailed questions and outstanding issues were clarified through email exchanges.

5. Case study: The Morgan motor Co

The Morgan Motor Company was founded in 1909, by Henry Frederick Stanley ('H.F.S.') Morgan, and started production of the three-wheeler, to which was added the 'classic' range of four wheeled cars from 1936 (i.e. 4/4, Plus 4, Roadster, 4 seater, Plus 8), using traditional steel chassis, and more recently the Aero range (i.e. Aero Supersports, Aero coupe, AeroMax, Aero 8), using modern bonded aluminium honeycomb chassis construction. Even more recently, a recreation of the three-wheeler was added to the range. Morgan uses standardised modules for late, customer-tailored configuration, resulting in high customer loyalty, waste minimisation, product longevity, product value and high brand reputation (Morgan and Bowden, 2008). Cars are designed and engineered in-house and assembled by hand, they feature unique traditional styling using coach-built technology and, by using mass produced powertrain modules, are able to combine this with the latest technology. Construction involves an aluminium-panelled ash frame body fitted to a steel or aluminium chassis. Engines, transmissions, rear axles and certain pressed (as opposed to hand-formed) body panels are outsourced. The interiors consist of hand-stitched leather over outsourced seat frames, polished hardwoods and advanced electronics technology (Morgan and Bowden, 2008). The Morgan business model relies on making low volumes of durable cars tailored to the requirements of individual customers. Morgan produces around 700–1300 cars a year and pitches its maximum production capacity below the level of minimum demand, thereby ensuring it permanently works at or near maximum capacity. It is able to take this approach, due to the fact it has few, if any true competitors; customers are therefore prepared to wait for their individually tailored vehicle. Fluctuations in demand are then managed by means of the length of the waiting list, i.e. the difference between supply and demand is mediated by time.

In general, the true nature of small-scale car manufacturing is not well understood. The mass production of cars as we know it today requires very large capital investments in three major processes: pressing, welding and painting. In addition, there is the actual final assembly process, which requires lower levels of investment, but is highly labour-intensive. What is termed a car 'assembly' plant is primarily involved in creating the car's steel body. This process, together with engine production, constitutes the major fixed cost for mass production. These can only be recovered with very high levels of production and sales. This in turn leads to rapid depreciation of new cars. This accelerated dissipation of economic value is a key factor in older cars becoming 'beyond economical repair' long before their technical 'end-of-life' (Nieuwenhuis, 2008). Morgan's business model avoids this altogether; Morgans have a very long service life, with older cars returned to the factory to be refurbished or rebuilt, allowing the company to capture some of the considerable value contained within the aftermarket part of the value chain.

Morgan sources engines from Ford and BMW, thus benefiting from the economies of scale achieved by these firms for their mass produced vehicles, while also enjoying the product development investments of these firms, including keeping up with developments in emissions control and other legislation (Table 1). Transmissions are sourced from ZF and Mazda, while rear axles are sourced from Dana's facility in Thailand. Chassis are steel for the traditional cars, sourced from ABT in nearby Ross-on-Wye, while aluminium chassis, as well as bulkheads are sourced from Radshape in Birmingham. Bodies are constructed in-house using

Table 1
Morgan supply chain (simplified).

External suppliers	Process	External suppliers
ABT, Ross-on-Wye (steel chassis frame)	CHASSIS	BMW, Eching, Germany (V8 engines)
Radshape, Aston, Birmingham (aluminium chassis frame)		Ford, Bridgend, Wales (4 and 6 cylinder engines)
Dana Spicer, Thailand (rear axles)		Mazda, Nakanoseki, Japan (gearboxes)
MWS, Slough (wire wheels)		ZF, Germany (gearboxes)
AP Racing, Coventry (brakes)		Boysen, Germany (exhaust)
Eibach, Finnentrop, Germany (springs)		
Radshape, Aston, Birmingham (bulkheads)	BODY	Superform, Worcester (wings/mudguards)
	PAINT	
Leather from Scotland and Yorkshire	TRIM	MB Components, Exeter (seat frames)
Bosch, Germany (electronics)		Serck Services, Coleshill (radiators)
		Mountney, Leighton Buzzard/Banbury (steering wheels)

traditional coach-built, ash-frame construction, to which hand-formed aluminium panels are fitted. These days, front mudguards are in super-formed aluminium on soft tooling by Superform in nearby Worcester. Cars are painted and trimmed in-house, thereby controlling all processes that matter to the customer and Morgan also directly controls all processes – notably body construction – that allow rapid and flexible evolution of models.

6. Discussion

The decoupling point concept was discussed in Section 3.1; the question now arises as to how this applies to this particular case study. The existing theory still presents only a partial picture in that it provides little detail of the determinants of the material decoupling point, particularly those affecting its location along the value chain. Different technologies used in the various manufacturing processes that form the key value adding parts of a supply chain or value chain have different levels of capital investment, and hence are subject to different economies of scale. By mixing and matching different technical solutions along the manufacturing stages of a value chain, the point at which what economies of scale occur can be moved, thereby allowing different degrees of leanness and agility at these different points in the value chain with consequent impact at other points along that value chain. However, in certain sectors, such as conventional automotive mass production, the scope for this is limited. In reality, this more than anything else determines the barriers to the free movement of the material decoupling point as presently understood, particularly in certain industries, such as automotive (Fig. 1).

Mass production is accepted as a *sine qua non* of the car industry; a notion undermined to some extent by the persistence of small scale car makers such as Morgan, particularly in mature markets. In reality, as Sabel and Zeitlin (1985, 1997) have argued, mass production itself was not an inevitable outcome of industrial history and historically a number of disparate factors had to come together in order to construct what we might now think of as the mass production system, or paradigm (Dosi, 1982) in cars. The role of Ford in this process is well established in the literature, though not always well understood. In reality, Ford pioneered the mass production of key mechanical components that allowed the mass production of what we would now think of as a powered chassis. Bodywork was outsourced by Ford and was considered a key bottleneck preventing the mass production of cars. This, and the role of Budd in solving the problems of mass producing all-steel car bodies, has been explored in considerable detail by Nieuwenhuis and Wells (1997, 2003, 2007), by Wynn-Williams (2009) and to a lesser extent by Orsato (2009). The final piece in this jigsaw was the creation of a mass market and we can attribute this to General Motors under Sloan and its combination of innovations such as large scale vehicle finance, trade-ins, offering of a model range, use of colour and trim and regular facelifts (Altshuler et al., 1984; Flink, 1988). The new-found economies of scale, determined by the technology choices made by Ford and Budd, initiated a trajectory that replaced labour with capital, created large, centralised assembly facilities requiring inbound and outbound logistics networks of great complexity, that separated manufacturing from retail and distribution, and supplied customers with more or less standardised products optimised for mass manufacturing at low per-unit cost.

Yet Ford himself recognised the danger of large concentrated facilities (Ford & Crowther, 1924, 84). Indeed, Ford used, for the Model T, a system of standardised, centralised component production plants, combined with dispersed assembly facilities; a modular approach much like modern CKD (complete knocked-down kit) operations. It was primarily the need for high capital equipment in the Budd all-steel body system – something Ford long resisted – rather than Ford's iconic moving assembly line, that led to the need for large, concentrated assembly plants in addition to large concentrated component plants. Hence, what Nieuwenhuis and Wells (2007) term the Fordist-Buddist model of mass car production became inherently a supply-driven rather than a demand-driven system. The fact is that it may be suited to steadily growing newly motorising markets, more accepting of standardised products, but that it struggles to handle the increasing demand for differentiation that comes with more mature markets. In addition it put the industry on an unsustainable trajectory of what amounts to chronic overproduction. To some extent the Toyota Production System was a way of addressing this issue, although it was still limited by the inherent inflexibility of Buddist all-steel body construction, an area where many of Toyota's innovation efforts – such as rapid die-change – were therefore concentrated.

This also suggests that there may be a more optimised way of making cars for such diverse and fragmented markets, that at the same time may also be significantly more sustainable due to its viability at much lower volumes i.e. a post-mass production system for cars. Essentially, the importance of technology choice on process has often been either overlooked, or indeed underplayed. Processes are the result of technology choices, that are themselves often determined by the product and in turn determine the balance between capital and labour. Where more capital-intensive processes

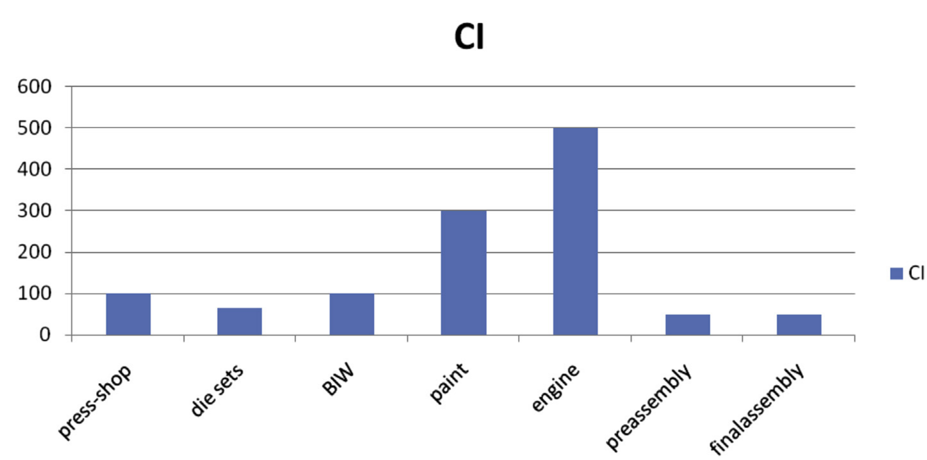

Fig. 1. Capital investments for value adding stages in mass car manufacturing (€000000s).
Source: adapted from data in Nieuwenhuis and Wells, 1997, 2003, 2007.

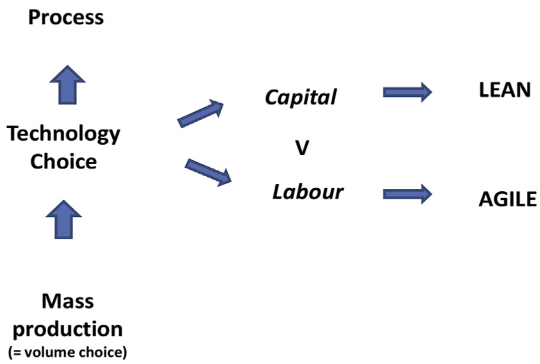

Fig. 2. How technology choice determines process.

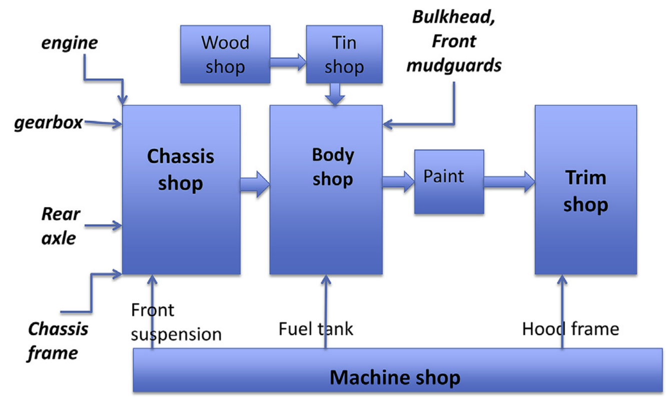

Fig. 3. Morgan supply chain.

are used, lean approaches tend to be more appropriate, while labour-intensive processes lend themselves more to agile approaches – material decoupling points are therefore constrained by this division. In the automotive context the choice for a mass production and mass market approach naturally leads to particular technology choices, which then determine the processes required (Fig. 2). Alternative approaches to car building, normally favoured by low volume producers, often allow greater agility by moving the leanest activities up the supply chain, while favouring more agile processes near the market.

In Fig. 1, press-shop, die sets, BIW (body-in-white = the phase where the pressed steel panels are welded together to form the unitary body), and paint are all to a large extent inherent elements of the Buddist system, thus they need to be considered in combination. By abandoning traditional Budd-style car body manufacturing in favour of some alternative, it may be possible to replace this key 'lean' phase with a more 'agile' one. Nieuwenhuis and Wells (2003) have shown that this difference in technology can lead to break-even points an order of magnitude lower than for conventional Budd-style construction; i.e. in the hundreds per year – as in the case of Morgan – rather than approaching 100,000 a year as is more typical for mass production (Table 2). It is clear from Fig. 1 that these high investment areas are paint and engine production. If we add the other processes dedicated to steel body production, the picture becomes clearer: the high investment technologies are engine and body. One possible option is to use a more modular technique or to use different materials that can be shaped in different, lower capital investment processes. In some cases, this allows the moving of those processes where capital investment is high and hence economies of scale important – and leanness practical – further up the supply chain, thus allowing more phases closer to the customer to become more agile and responsive.

In the case of the specialist car sector, what allows firms like Morgan to operate in a competitive market environment at low volumes is the combination of factors outlined above; they have moved economies of scale in powertrain outside their own operations by moving their manufacture – and hence material decoupling point – up the supply chain by sharing engines, axles and transmissions with mass produced models (Fig. 3). Second, they have abandoned or, in the case of Morgan, never adopted capital-intensive Budd all-steel body construction and instead selected a number of alternative solutions, in Morgan's case traditional ash-framed coach-built bodies and bonded aluminium construction. The relatively low volumes still attract a cost penalty reflected in the relatively high price level of these cars, however, Morgans are cost-competitive with most equivalent mass produced sports cars, while their exclusivity and durability and the resulting high residual values, would in any case justify a price premium in the market. Ultimately, as these are essentially cars with labour to some extent replacing capital, there is no real reason why their price level should be lower than mass produced cars and clearly customers are willing to pay these prices and residual values are strong. This can also be linked with the findings of Hallgren and Olhager (2009), whose detailed empirical study of – among other sectors – 73 automotive suppliers finds that were cost leadership is pursued, lean is always preferred. Morgan favours differentiation, not cost-

Table 2
Assembly facility comparison: Conventional Mass Car Production vs Leagile Car Production.

	Conventional Mass car manufacturing	Leagile car production	Advantages
Typical capital investment	USD 1.7bn/plant	USD 30 mn/plant	Lower costs of entry and exit
Typical capacity per plant	250,000/year	5000/year	Much more scalable system, adaptive to market demand
Breakeven point (annual units produced)	100,000	500–1000 (depending on technology)	More economic resilience
Typical labour per plant	3000–4000	200–300	More localised employment; less impact on local communities from plant closure
Cars/worker/year (at capacity)	62.5	16.6	Much higher labour input and job content
R&D cost per model	USD 850 mn	USD 20 mn	Much more scope for low volume innovative products
Model specific tooling	USD 850 mn	USD 8.5 mn	Risk of failure of a novel technology model much lower; cost of replacement much lower
Supply chain	Large number of component and specialist module suppliers	Local suppliers of specific parts; core modules standardised and sourced from large centralised facilities	Conventional economies of scale retained for core modules (e.g. powertrain); great flexibility for other components

Source: Centre for Automotive Industry Research, Cardiff University.

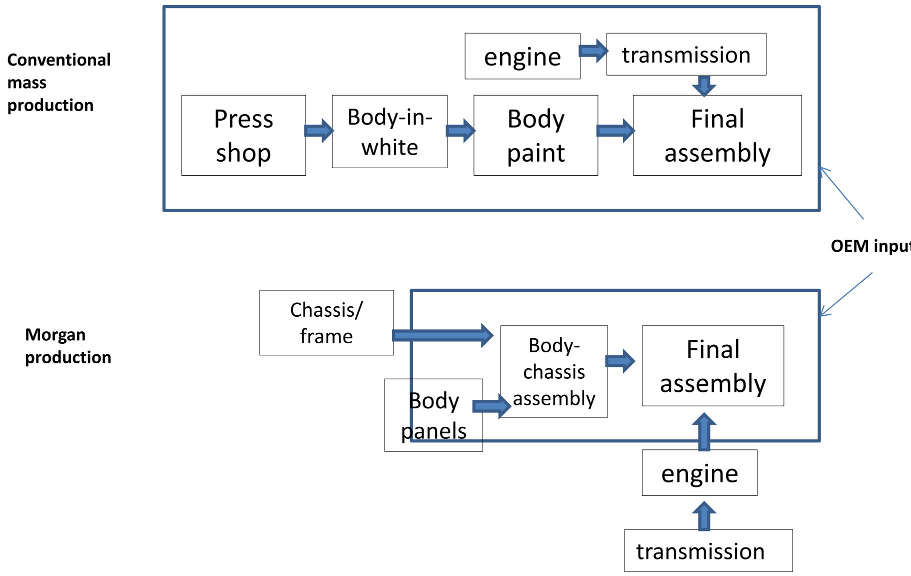

Fig. 4. Conventional vs Low Volume Car Production.

leadership and, following these findings, an agile approach is therefore appropriate. In Morgan's case the leanness is then the realm of its suppliers.

Fig. 4 shows the fundamental differences in approach that ensure the viability, at low volumes, of the specialist car sector, specifically Morgan, as compared with conventional mass car production. It is shown, first of all, that in this alternative model, engine and transmission are outsourced, thereby moving the decoupling point up the supply chain. In the key area of vehicle assembly, there are also significant differences with a much lower level of vertical integration in the sector, as well as the different technology choices outlined earlier, which – among other benefits – avoids the need for a press shop (replaced with manual craft skills and low cost generic tooling), body-in-white (replaced by ash and metal fabrication processes), while the paint shop relies on human labour rather than robots. The 'chassis frame' and 'body panels' boxes in Fig. 4 straddle the OEM box, as different degrees of vertical integration can be observed; the front mudguards or fenders and bulkheads, for example, are outsourced even though most of the body is built in-house. The information decoupling point is controlled by Morgan which is able to simply order standardised powertrain and chassis frame modules from suppliers as and when required; as the volumes Morgan needs have a marginal impact on the production planning of their mass-production suppliers. Table 2 highlights the key advantages of such an approach from an economic, social and environmental, or sustainability and resilience perspective, based on our research.

While the transition to such a manufacturing system would not be easy, it would nevertheless create a degree of resilience within the automobility system that the current mass production regime does not possess.

7. Conclusions

The main approach that emerges from the 'lean and green' literature so far, as analysed by observers such as Martinez-Jurado and Moyano-Fuentes (2014), is one of eco-efficiency; i.e. doing the same thing, making the same products or providing the same services, but in a more efficient, less wasteful manner. The essence of the product, service, or production system is not usually questioned. In our move towards more sustainable production and consumption, we need to consider the next step: how can we meet our actual needs and wants, or perceived needs and wants in a more sustainable manner, with products that are more sustainable and using production systems that are more sustainable? The present contribution has been an attempt to explore this in the context of motorised personal mobility – the automobile – but delivered in a more sustainable manner. The method chosen is a case study of a small firm that already is some way along such a trajectory and using the latest thinking in lean and agile, or 'leagile' value chains to propose a way of delivering this.

In terms of vehicle structures, the economics of traditional all-steel body construction have been analysed, principally by Nieuwenhuis and Wells (1997, 2003, 2007). This system involves very high tooling costs per model variant, and very high investments in press technology, as well as special paint and surface treatment technologies. Morgan avoids this by using alternative technologies as outlined above. Essentially, there appears to be a need in the case of certain manufacturing processes – in this case automotive – for a deeper understanding of determinants of the location of the material decoupling point. It is shown here, that this is often defined by major areas of capital investment, notably – in automotive – by powertrain and body/chassis structure. The specialist sports car producers such as Morgan move the material decoupling point, but not the information decoupling point up the supply chain by limiting their own in-house activities. They outsource modular components in a potentially lean fashion from suppliers, while retaining control of the customer-facing activities, thereby being able to operate in an agile fashion in those key value-added areas they retain in-house. In Fig. 4, both the material and information decoupling points are on the boundary of the OEM 'box'. However, more significant is the extent to which firms like Morgan manage the material decoupling point by both moving this up the supply chain, allowing suppliers to work 'lean' while they remain 'agile', but also by opting for technology choices, notably in body/chassis construction that require significantly lower levels of capital investment in the first place, thereby allowing greater freedom in where to locate the material decoupling point.

The argument here is that a deeper understanding of barriers to the free movement of the material decoupling point in the manufacturing system and of the ways in which this forces manufacturers to overproduce, is essential for developing future more environmentally sustainable supply chains. The need for which arises from the present unsustainable nature of mainstream mass car production and the steady shift in carbon intensity – as a result of technology trends – from the use phase to the manufacturing phase. The potentially more agile system used by specialist firms such as Morgan could be developed into a system with greater market responsiveness than the prevailing mass production system thereby avoiding overproduction, while at the same time reducing the reliance on high volume manufacturing of complete cars rather than core modules that current mass producers suffer from. Such a system could, for example, involve the mass production of core components and subassemblies to be shared as virtual commodities by a range of smaller low investment assemblers. This would be in line to some extent with what is suggested in the context of the Micro Factory Retailing model by Nieuwenhuis and Wells (2003), Wells and Nieuwenhuis (2000, 2004) and Wells (2001, 2004, 2010), although these contributions offer little detailed information as to how such a model might be achieved in practice.

The result of the findings here is that it provides the scope for creating a more economically viable automotive industry that is potentially more sustainable with more positive social and environmental impacts. It should also be noted that the additional choice – beyond what mass manufacturers are able to offer – presented by these specialist cars has been possible only because of the way the manufacturing system operates. To this extent, therefore, this is an example of increased agility and enhanced market responsiveness through what is primarily an alternative manufacturing model, albeit one with the potential to be expanded into a full alternative, more sustainable business model. The implications of this for future supply chains are deserving of further investigation.

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References

Aguado, S., Álvarez, R., Domingo, R., 2013. Model of efficient and sustainable improvements in a lean production system through processes of environmental innovation. J. Clean. Prod. 47, 141–148.
Alford, D., Sackett, P., Nelder, G., 2000. Mass-customisation – an automotive perspective. Int. J. Prod. Econ. 65, 99–110.
Altshuler, A., Anderson, M., Jones, D., Roos, D., Womack, J., 1984. The Future of the Automobile. Allen & Unwin, London.
Brabazon, P., MacCarthy, B., Woodcock, A., Hawkins, R., 2010. Mass customization in the automotive industry: comparing interdealer trading and reconfiguration flexibilities in order fulfillment. Prod. Oper. Manag. 19 (5), 489–502.
Cheney, G., Wilhelmsson, M., Zorn, T., 2002. 10 Strategies for engaged scholarship. Manag. Commun. Q. 16 (1), 92–100.
Childerhouse, P., Towill, D., 2000. Engineering supply chains to match customer requirements. Logist. Inf. Manag. 13 (6), 337–345.
Christopher, M., Towill, D.R., 2000. Supply chain migration from lean and functional to agile and customized. Supply Chain Manag. An Int. J. 5 (4), 206–213.
Christopher, M., Towill, D.R., 2001. An integrated model for the design of agile supply chains. Int. J. Phys. Distrib. Logist. Manag. 31 (4), 235–246.
Christopher, M., Towill, D.R., 2002. The supply chain strategy conundrum: to be lean or agile or to be lean and agile? Int. J. Logist. Manag. 5 (3), 299–309.
Christopher, M., Towill, D.R., 2007. Don't lean too far – evidence from the first decade. Int. J. Agile Syst. Manag. 2 (4), 406–424.
Cooper, T., 2005. Slower consumption; reflections on product life Spans and the "Throwaway Society". J. Ind. Ecol. 9 (1–2), 51–67.
De Groot, M., McCrossan Maire, B., 1998. Collector's car and marketing of new vehicles: the Case of Daimler-Benz AG. In: Kostecki, M. (Ed.), The Durable Use of Consumer Products. Kluwer, Dordrecht, pp. 113–118.
Doran, D., Hill, A., Hwang, K.-S., Jacob, G., 2007. Supply chain modularization: cases from the French automobile industry. Int. J. Prod. Econ. 106, 2–11.
Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Res. Policy 11, 147–162.
Dües, C., Tan, K.H., Lim, M., 2013. Green as the new lean: how to use lean practices as a catalyst to greening your supply chain. J. Clean. Prod. 40, 93–100.
Feitzinger, E., Lee, H.L., 1997. Mass customization at Hewlett-Packard: the power of postponement. Harv. Bus. Rev. 75 (1), 116–121.
Flink, J., 1988. The Automobile Age. MIT Press, Cambridge.
Ford, H., Crowther, S., 1924. My Life & Work, second ed. Heinemann, London.
Hallgren, M., Olhager, J., 2009. Lean and agile manufacturing: external and internal drivers and performance outcomes. Int. J. Oper. Prod. Manag. 29 (10), 976–999.
Hawkins, T., Singh, B., Majeau-Bettez, G., Hammer Strømman, A., 2012. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 17 (1), 53–64.
Hoekstra, S., Romme, J., 1992. Integrated Logistics Structures: Developing Customer Oriented Goods Flow. McGraw-Hill, London.
Krishnamurthy, R., Yauch, C.A., 2007. Leagile manufacturing: a proposed corporate infrastructure. Int. J. Oper. Prod. Manag. 27 (6), 588–604.
Martinez-Jurado, P., Moyano-Fuentes, J., 2014. Lean management, supply chain management and sustainability: a literature review. J. Clean. Prod. 85, 134–150. http://dx.doi.org/10.1016/j.jclepro.2013.09.042.
Mason, R., Nieuwenhuis, P., Simons, D., 2008. Lean and green supply chain mapping; adapting a lean management tool to the needs of industrial ecology. Prog. Indu. Ecol. – An Int. J. 5 (4), 302–324.
Mason-Jones, R., Towill, D.R., 1999. Using the information decoupling point to improve supply chain performance. Int. J. Logist. Manag. 10 (2), 13–26.
Mason-Jones, R., Naylor, B., Towill, D., 2000. Engineering the leagile supply chain. Int. J. Agile Manag. Syst. 2 (1), 54–61.
Maxton, G., Wormald, J., 2004. Time for a Model Change; Re-engineering the Global Automotive Industry. University Press, Oxford.
Morgan, C., Bowden, G.H., 2008. Morgan 100 Years; the Official History of the World's Greatest Sports Car. Michael O'Mara, London.
Moyano-Fuentes, J., Sacristán-Díaz, M., 2012. Learning on lean: a review of thinking and research. Int. J. Oper. Prod. Manag. 32 (5), 551–582.
Moyano-Fuentes, J., Sacristán-Díaz, M., Martínez-Jurado, P., 2012. Cooperation in the supply chain and lean production adoption; evidence from the Spanish automotive industry. Int. J. Oper. Prod. Manag. 32 (9), 1075–1096.
Naim, M., Barlow, J., 2003. An innovative supply chain strategy for customized housing. Constr. Manag. Econ. 21 (6), 593–602.
Naylor, J.B., Naim, M., Berry, D., 1999. Leagility: integrating the lean and agile manufacturing paradigms in the total supply chain. Int. J. Prod. Econ. 62 (1–2), 107–118.
Nieuwenhuis, P., 1994. Environmental implications of just-in-time supply in Japan – lessons for Europe? Logist. Focus (April), 2–4.
Nieuwenhuis, P., 1994b. The long-life car: investigating a motor industry heresy. In: Nieuwenhuis, P., Wells, P. (Eds.), Motor Vehicles in the Environment; Principles and Practice. John Wiley & Sons, Chichester, pp. 153–172.
Nieuwenhuis, P., 2008. From banger to classic – a model for sustainable car consumption? Int. J. Consum. Stud. 32 (6), 648–655.
Nieuwenhuis, P., 2014. Sustainable Automobility; Understanding the Car as a Natural System. Edward Elgar, Cheltenham.
Nieuwenhuis, P., Wells, P., 1997. The Death of Motoring?; Car Making and Automobility in the 21st Century. John Wiley, Chichester.
Nieuwenhuis, P., Wells, P., 2003. The Automotive Industry and the Environment – a Technical, Business and Social Future. Woodhead, Cambridge.
Nieuwenhuis, P., Wells, P., 2007. The all-steel body as a cornerstone to the foundations of the mass production car industry. Ind. Corp. Change 16 (2), 183–211.
OECD-MIT, 1994. In: Experts Seminar on Sustainable Consumption and Production Patterns, Massachusetts Institute of Technology, Cambridge, Mass., 18–20 December. Summary Report, URL. http://www.iisd.ca/consume/mit.html (March 2014).
OICA, 2014. 2012 production Statistics. www.oica.net/category/production-statistics/2012-statistics/ (February 2014).
Orsato, R., 2009. Sustainability Strategies: when Does it Pay to Be Green? Palgrave Macmillan, London.
Porsche, 1976. Long-life Car Research Project: Final Report Phase I; Summary. Dr Ing h c F Porsche AG, Stuttgart.
Ricardo for the Carbon Trust, 2011. International Carbon Flows – Automotive. Carbon Trust, London. www.carbontrust.com/media/38401/ctc792-international-carbon-flows-automotive.pdf (June 2014).
Romm, J., 1994. Lean and Clean Management; How to Boost Profits and Productivity by Reducing Pollution. Kodansha, Tokyo.
Sabel, C., Zeitlin, J., 1985. Historical alternatives to mass production: politics, markets and technology in nineteenth-century industrialization. Past Present 108, 133–176.
Sabel, C., Zeitlin, J. (Eds.), 1997. World of Possibilities; Flexibility and Mass Production in Western Industrialization; Studies in Modern Capitalism. University Press, Cambridge.
Stahel, W., Reday-Mulvey, G., 1981. Jobs for Tomorrow, the Potential for Substituting Manpower for Energy. Vantage Press, New York.

Stratton, R., Warburton, R., 2003. The strategic integration of agile and lean supply. Int. J. Prod. Econ. 85 (2), 183–198.
UN, 1997. Preparations for the Special Session of the General Assembly for the Purpose of an Overall Review and Appraisal of the Implementation of Agenda 21. UN Economic and Social Council, New York. E/CN.17/1997/19, 24 February.
Van de Ven, A., 2007. Engaged Scholarship; a Guide for Organizational and Social Research. University Press, Oxford.
Van de Ven, A., Johnson, P., 2006. Knowledge for theory and practice. Acad. Manag. Rev. 31, 802–821.
Vinodh, S., Arvind, K.R., Somanaathan, M., 2011. Tools and techniques for enabling sustainability through lean initiatives. Clean Technol. Environ. Policy 13 (3), 469–479.
Walker, B., Salt, D., 2006. Resilience Thinking; Sustaining Ecosystems and People in a Changing World. Island Press, Washington.
Wells, P., 2001. Micro factory retailing: a radical new product, manufacturing and marketing strategy for the automotive industry. In: Pham, D.T., Dimov, S.S., O'Hagen, V. (Eds.), Advances in Manufacturing Technology. Professional Engineering Publishing Ltd, London.
Wells, P., 2004. Creating sustainable business models: the case of the automotive industry. IIMB Manag. Rev. 16 (4), 15–24.
Wells, P., 2010. The Automotive Industry in an Era of Eco-austerity; Creating an Industry as if the Planet Mattered. Edward Elgar, Cheltenham.
Wells, P., Nieuwenhuis, P., 2000. Why big business should think small. Automot. World July/August 32–38.
Wells, P., Nieuwenhuis, P., 2004. Decentralisation and small scale manufacturing: the basis of sustainable regions? J. Environ. Plan. Policy 6 (3/4), 191–205.
Wells, P., Nieuwenhuis, P., 2012. Transition failure: understanding continuity in the automotive industry. Technol. Forecast. Soc. Change. http://dx.doi.org/10.1016/j.techfore.2012.06.008, 27th July 2012.
Womack, J., Jones, D., 1996. Lean Thinking; Banish Waste and Create Wealth in Your Organization. Simon and Schuster, London.
Womack, J., Jones, D., Roos, D., 1990. The Machine that Changed the World. Rawson, New York.
Wong, W.P., Wong, K.Y., 2014. Synergizing an ecosphere of lean for sustainable operations. J. Clean. Prod. 1–16. http://dx.doi.org/10.1016/j.jclepro.2014.05.093.
Wynn-Williams, M., 2009. Surfing the Global Tide; Automotive Giants and How to Survive Them. Palgrave-Macmillan, Basingstoke.