Radical Re-Modularization: Tradeoffs in Designing Mass Customization Product Architectures

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Key words
Re-Modularization, Product Architecture, Mass Customization, Concept Car

Abstract
The rise of mass customization has led to changes in supply chain management, openness to customer co-design, and an emphasis on flexible and modular product architectures. The search for better, more compact and efficient modules and product families places a heavy emphasis on compartmentalized customization strategies consisting of cosmetic skins, both large and small plug-in electronics and interior modules, ergonomic treatments, and battery storage. Such strategies allow for endless variation in the elements deemed most meaningful to the customer. However the tradeoffs can lead to wastefulness in materials, poor packaging, issues with structural integrity, and postponement in the fabrication of elements until user preferences are determined.

Radical re-modularization is the complete rethinking of product architectures into multilayered and multifunctional product building blocks. Emphasis is placed on the integration of apparently disparate components into new configurations while capturing dual-functionality both at the subcomponent and system level. This paper chronicles the development of a new vehicular architecture following the principles of radical re-modularization and the tradeoffs that result. The research centers upon the developments within the MIT Media Lab's Concept Car project with General Motors.

Our development of modular “Wheel Robots” that incorporate embedded electric motors, braking systems, and suspension within the wheel hub allows for a new architecture and a new model of design and manufacture. At a minimum, one quarter of the drivetrain is embodied with a wheel-motor unit, thus allowing the complete separation and customization of the chassis and body of the vehicle. The Wheel Robots perform all the functions of steering, braking, and acceleration. Upgrades to the vehicle can be executed by swapping out any or all of the wheel units. The future manufacture of vehicles can thus be distinctly divided into the creation of 1) standard Wheel Robots that are highly optimized, flexible, and configurable by digital mediation, and 2) highly customized
chassis and body solutions. The Wheel Robots can be mass produced; while the remainder of the vehicle can be produced using highly localized manufacturing thus benefiting from advances in computer aided design and manufacture (CAD/CAM). The radical re-modularization of existing product architectures produces a new model of mass customization with flexible customization at the cosmetic, electronic, ergonomic, and structural level.

1 Introduction

Radical Re-Modularization is the process of examining existing product architectures at the highest levels in order to re-organize key components at lower levels of the product structure to create either more integrated or more modular solutions that will yield new benefits. This paper discusses a new vehicle architecture based on the creation of electric wheel motors with embedded suspension called “Wheel Robots” which enable a high level of customization for the body and passenger cabin. We will then discuss the tradeoffs that result when implementing this architecture. A main driver to this process has been the development of a vehicle that epitomizes the design principles of mass customization. The Concept Car project became the testing platform and a virtual sounding board to illustrate these ideas.

The emergence of new product architectures in mature products like cars is limited because of the large capital investment needed to design, engineer, evaluate, adjust, and refine a new vehicle platform. Automotive product development has historically taken an evolutionary track influenced by 1) developments in propulsion systems, 2) innovations in mechanics, 3) use of new materials, 4) improved manufacturing techniques, and 5) market forces. In addition to incremental improvements in these areas, a number of key product architectural configurations were developed throughout automotive history. Front-engine, mid-engine and rear-engine configurations all presented differing challenges to the passenger cabin, drive train configuration, and overall form and style of the vehicle.

Most recently the GM AUTOonomy in 2002 introduced a new form of architecture. The AUTOonomy placed the electric motor wheels, HVAC, fuel cell stack, and safety elements in a sandwich-like thin skateboard platform. The passenger cabin would be connected to the skateboard to form the completed vehicle. This "Radical Re-modularization" of the vehicle architecture created a number of benefits such as complete freedom in the design of the body, separation of driving mechanicals from the body, and the separation of the chassis and body. The designers of the AUTOonomy point to a reorganization of not only the architecture of the vehicle but the business of manufacturing it and the infrastructure needed to support it. 1 AUTOonomy and our project which is based on even finer and smaller product modules speculate on a highly adaptive and flexible platform that can be reconfigured.

The automobile industry historically has relied on product platforms which can be modified to create a families of vehicles. This iterative process builds upon previous knowledge base both within
companies and outside (through benchmarking). However, mature products with more complex and longer product lifecycles need to be re-examined. The development of electronic products like cell phones, PDAs, laptops, and other electronics has proven that a flexible product architecture built upon interchangeable modular components is vital to creating many variants, yet still yield large quantities in production. Over time, open source design and the development of new supply chains will enable manufacturers to design with more variety at both cosmetic and electronic levels.

2 Customization

The influence of mass customization in the global economy has increased the importance of creating highly personalized and customizable products. Intelligent supply chains allow for greater variety by reducing the inventory of materials and just-in-time manufacturing combined with the ability to postpone customer centric components until the final stages of assembly allow for a high level of customization. To discern different levels of customization it is necessary to divide these characteristics into several categories or "Customization Typologies." A product can be customized to one, all, or a combination of differing degrees. These are 1) cosmetic, 2) electronic, 3) ergonomic, 4) structural, and 5) material.

2.1 Cosmetic Customization

Cosmetic customization is concerned with the design of surfaces, packaging and general presentation of a product. Being able to customize cosmetically allows manufacturers the ability to tailor colors to current trends and user preferences. In the case of consumer electronics with short lifecycles, manufacturers have incorporated new technologies to provide a high level of cosmetic customization. For example, cell phones can be customized by submitting images through a website to be imprinted onto the phone.

2.2 Electronic Customization

Consumer electronics like PDAs and cell phones are electronically customizable through wireless connections like Bluetooth, cellular networks, Wifi, WiMax, and others. Mobile phones can map different ring tones to different callers. MP3 players allow listeners to customize play lists by a multitude of ways such as most recent, last added, most played, random selection, and so on. Flexible software architectures allow for high levels of customizability in any electronic product. The advent of open source software allows for users to build customized modules which can be improved by others over time. The need to modify and personalize by lead users has created a very large aftermarket industry. The range of electronic customization is vast, ranging from ipod adapters to performance-enhancing chips that control engine performance.

2.3 Ergonomic Customization

Adapting to the constraints of the human body connects the product anatomically to the user. Computer mice are often contoured to fit a range of hand sizes. Cell phone buttons and casings are designed to allow users easy button access, comfort in holding the device, and compactness when in
the pocket. At the full human scale, the Aeron chair by Hermann Miller pushed ergonomic configurability for office furniture. In cars, memory seats combine both electronic and ergonomic customization by manipulating the seat to fit your ergonomic preferences electronically. Often cars with such a feature have different memory settings for different drivers for the same car.\textsuperscript{6}

\subsection*{2.4 Structural Customization}

The ability to adapt or customize a product given different loading conditions characterizes a high level of structural customization. Certain tractor trailers can adapt to the length of the payload, so that a universal shipping container in Japan can fit on a North American vehicle. Office cubicles (in a modular fashion) can be configured to offer a new office structure of either openness or privacy.\textsuperscript{7} The foldable structures of Santiago Calatrava are highly customizable by structural standards as they are able to adapt to not only changing structural loads but also to site-specific conditions of light, circulation, and access.

\subsection*{2.5 Material Customization}

Material customization offers a myriad of choices not only to the finish, but to the major composition of the product. Ideally, material customization adds value cosmetically, but also performs in a structural, acoustic, or conductive (electrical) manner. Material customer choices have traditionally been trend-driven in the automotive industry. Vinyl was the new material for the masses in the 1970s and it became part of the car culture of that time. Ultra-lightweight and strong carbon fiber composites have been used in high performance vehicles because of their structural advantages and have found their way into interiors of high-end cars like Ferraris, Porsches, and Lamborghini, replacing metals and woods for interior panels and exterior body panels.\textsuperscript{8}

\subsection*{2.6 Combinatorial Customization Strategies}

Displays combine electronic and cosmetic customization effectively to convey visual material. Programmable displays like Electronic Ink (E ink) have the highest level of customizability because they combine the maximum benefits of each typology. If the driver desired to personalize his dashboard, traditional analog displays offer little flexibility. Programmable and flexible displays enable the user to completely customize every surface enabled by such technologies.

Sound systems are electronic devices. However, the ability for a sound system to be customizable is a combination of electronic, structural, and material qualities. How sound travels through space and refracts on and off surfaces depends very much on the material qualities and the spatial configuration of the environment. The density and acoustic qualities of the surfaces in contact with sound waves either amplify or dampen acoustic energy.

Haptic feedback systems are a combination of electronics, material, and ergonomic customization typologies. Keyboard keys possess force feedback so that the typist knows a letter has been typed. Ergonomics is a critical component in keyboard because the human hand has areas of more and less sensitivity. Good haptic feedback systems take advantage of those differences. The F and J keys on
North American keyboards have small raised tabs so that you can orient your hands without looking at the keys. Additionally, the type of material dramatically impacts haptic systems. A highly customizable haptic feedback system will capitalize on the subtle noticeable sensitivities in the human nervous and perceptive system.

3 Principles of Radical Re-Modularization

Radical Re-modularization examines existing product architectures in order to re-organize assemblies and sub-assemblies in new configurations that yield novel benefits. Digital cameras exemplify this methodology because the replacement of analog film recording with digital recording now allows for very thin form factor. Often the reorganization of the product architecture will create less integrated, more modular solutions which have a number of benefits and detractors.

At the highest levels, vehicle architectures can be classified according to location of the engine: front, middle, or rear. This has drastic implications for performance, cabin layout, and overall form of the vehicle. Other critical elements such as suspension components, storage, fuel tank, HVAC, and exhaust systems also affect the packaging of the vehicle. This complex interweaving of components yields a complete vehicle. To gain a better understanding of product architectures, we will utilize a product tree to describe relations between the parts of the whole. Although there are numerous interpretations, we will use this method of diagramming to illustrate product structures and syntax at a high level.

Below is a simple tree diagram of a traditional car layout. Figure 1 is a primarily a 3 level expansion of a traditional car layout (Internal Combustion Engine). This base diagram will serve as a starting point in deriving a multitude of vehicle architectures, including the AUTOonomy, Electric car, and our Wheel Robot architecture.
Effective Re-Modularization changes high level product architectures. This often occurs when new technologies are introduced into the system equation. The GM AUTOonomy platform distinctly divides into a skateboard platform and a separable body unit. The introduction of wheel motors in combination with a hydrogen based powerplant and fuel storage frees the passenger cabin from traditional constraints such as drive lines, engine blocks, and other mechanicals. The long term promise of the AUTOonomy platform is the separation of manufacturing paths for these components. The skateboard can be mass produced at key global centers whereas the bodies can be produced using a distributed and regional strategy with high levels of customizability.

Figure 1: Expanded Tree Diagram for Traditional Car

Figure 2: GM AUTOonomy Skateboard Chassis and Body
The AUTOnomy consists of a detachable body which can be designed specifically for passenger requirements and a skateboard with the following components 1) universal docking connection, 2) control system, 3) body attachments, 4) wheel motors, 5) fuel cell system, 6) heat dissipation, 7) rear and front crush zone. The expanded tree diagram below (Figure 3) shows the distinct separation between the skateboard chassis and the body.

![Figure 3: Expanded Tree Diagram for AUTOnomy Car](image)

### 3.1 Derivation of the Wheel Robot Architecture

The Wheel Robot is a fusion of electric drive, steering motors, and suspension elements into the hub of a wheel. Similar to the AUTOnomy architecture, Wheel Robots radically simplify the vehicle architecture into two distinct units 1) Wheel Robots and 2) everything else. Everything else in this case is the chassis (supporting structure) and passenger cabin. The following steps illustrate the Wheel Robot Derivation.

1. **Step 1:** Expanded tree diagram (existing)
2. **Step 2:** Select candidates for substitution or integration (re-modularizing stage)
3. **Step 3:** Reorganize tree
4. **Step 4:** Integrate and create new product architecture

We have identified key components that are prime candidates for substitution. The key factor in this stage is the recognition that emerging new technological trends redefine the constraints of the problem. For example, electric motors have made vast strides in efficiencies not because of the success of electric vehicles, but primarily due to better manufacturing techniques and the hybrid powered vehicle demand. Electric motors have excellent torque efficiencies as compared to internal combustion engines and other propulsion systems. In addition to developments in electric motors, drive-by-wire systems reduce the need for mechanical linkages. Fly-by-wire, throttle-by-wire, brake-by-wire systems have been well established in the aerospace and automotive industries. Combining
these factors allows the design team to explore the possibility of replacing a traditional drive train with 4 electric wheel motors that give direct power and steering to each wheel through digital control. This crucial research allows for the re-modularizing of the vehicle.

Once the key components have been recombined, the tree can be reorganized and redundancy in the system can be trimmed. No longer are a traditional powerplant and its associated subsystems needed. The new architecture created presents new opportunities and challenges which we discuss in the trade-offs section. With independent and digitally controlled Wheel Robots, the vehicle also does not need differentials, drive shafts and traditional transmissions.

In the diagram below, the components within the area marked by the dotted line represent the drivetrain elements that are being replaced by the Wheel Robots, with the remaining subsystems marked in red.

Figure 4: Wheel Robot Derivation Tree Diagram

The distinct differences between the AUTOonomy and the Wheel Robot architecture are a matter of scale and dividing lines in the product tree. The resulting diagram below shows a high level shift of the body towards the chassis and the integration of all drivetrain elements in the area of the wheel assembly.
Wheel Robots are self-contained, digitally controlled wheel motor units that perform all drive-train functions, such as steering, braking, acceleration, spring, and damping, thus freeing the chassis of the vehicle of these components. Similar to a USB stick and other electronics, the Wheel Robots require three connections to the chassis: 1) power, 2) signal, and 3) mechanical connection. Traditional mechanical control linkages have been replaced by electronic ones, which are much more compact, concentrated, and, like the wheel robots, easy to swap in and out.

An array of sensors embedded in the Wheel Robots allow the vehicle to comprehend the 1) grip force between the tire and the road, 2) air pressure for the proper balance, 3) suspension load and 4) road geometries. Traditional vehicle platforms require a series of mechanical set-ups, tuning, and testing before the vehicle dynamics are predictable enough to be aided digitally. In contrast, Wheel...
Robots distinctly solve the problem by allowing a reconfigurable architecture dependent on highly reactive and adaptive algorithms to work in concert to control the vehicle.

### 4.1 Modularity

Wheel Robots are designed with simple snap-on connections that operate in a “plug-n-play” fashion. This modular platform allows for easy replacement of entire wheel assemblies. Damaged Wheel Robots can be repaired by extracting the entire unit which can then be replaced with a new one, while the damaged Wheel Robot can be sent back to the manufacturer or repaired locally. Performance upgrades can be swapped-in.

### 4.2 Omni Directional Steering

Several design iterations have included full Omni-directional steering capable of 360 degrees of movement. This was spurred by the need to add high degrees of maneuverability given the urban driving conditions of this vehicle. Omni-directional movement allows the vehicle at low speeds to rotate all the wheels in order to pivot and translate. This is ideal for parallel parking into tight parking spaces. At higher speeds, Wheel Robots can limit steering movement in order to maintain stability.

### 4.3 Wheel Robot Families

Highly modular product architectures have been employed by manufacturers in order to allow for flexible assembly sequences and enable late-installation of customer/user centric components. Wheel Robots can be scaled in order to create a family of solutions. For large vehicles like trucks or tractor trailers Wheel Robots may not need to have Omni-directional steering, but perhaps require better transmission of power for hauling large loads. Wheel Robots for small cars need to be compact and require smaller braking systems and tighter overall packages. Medium sized Wheel Robots can possess a balanced hybrid of steering, braking, and acceleration abilities. Such families of Wheel Robots thus drive the manufacturing process to have highly standardized connections between chassis and connecting drive modules.

Figure 7: Full Scale, Running Wheel Robot Prototypes Built by Patrik Künzler, Raul-David “Retro” Poblano, and Peter Schmitt
5 Body Cabin

Unlike the aftermarket industry where tuners spend many man hours "modifying" vehicles, we can begin to imagine customizing the overall form of the vehicle. An intelligent parametric model can be created that would account for safety and other road-worthiness constraints and compute large number of possible envelope solutions. Utilizing CAD/CAM technologies, low production runs are possible thus allowing an extremely high level of customization. The cabin can be completely personalized from the outside in, given the user's ergonomic profile and cosmetic preferences. Let us now look at the cabin through the following view points: Manufacturer, Dealer/Distributor, and user.

5.1 Manufacturer

Manufacturers can maintain administrative control by producing Wheel Robot manufacturing centers in a few key locations. The production of the chassis and bodies can be widely distributed throughout the world through regional centers. Much higher levels of personalization are possible given the local economies of scale and access to site-specific material supplies. The Wheel Robot architecture simplifies the structure of the body thus promoting alternative materials such as composites, woods, and other natural materials amicable to localized design and fabrication. Wheel Robots by default create standards for connectivity both physically and electronically. A coupled modular and standardized approach allows for the customization of real value areas which the manufacturer acts as an integrator. Promoting this method of manufacture reduces excessive inventory if proper supply chains are present and user preferences are tracked and designs are executed.

5.2 Dealer

Car dealers and distributors can cater more specifically to their customers by presenting a kit-of-parts approach to vehicle configurations. Dealers can become centers of design by offering customization strategies to consumers and mediate the personalization experience. Repairs and maintenance is drastically improved because of the modular architecture: The dealer can quickly and simply swap out Wheel Robots.

5.3 User

The end user can customize the entire experience starting from the purchase to modifications after purchase. Performance upgrades to the Wheel Robots are simple given the standardized attachment points. The vehicle can be personalized based on human factors such as body ergonomics or social configurations deemed necessary by the consumer. The consumer might also be able to swap Wheel Robots.

6 Tradeoffs

Moving towards mass customized architectures provides many benefits to each player in the product lifecycle. Simultaneously, a number of tradeoffs result when a highly modular and personalizable system is put in place. This chapter discusses the tradeoffs that result in comparison to traditional car
architecture or that of an electric vehicle to the Wheel Robot architecture. This itemized comparison below looks at the number of components utilized for acceleration, steering, and braking, from the driver’s control input to the tire.

<table>
<thead>
<tr>
<th></th>
<th>Traditional Car</th>
<th>Electric Car</th>
<th>Wheel Robot Car</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceleration</strong></td>
<td>pedal, mechanical / electronic linkage to throttle, intake system, fuel tank, fuel lines, engine, exhaust system, transmission, differentials, drive shafts, suspension, wheel hub, wheel</td>
<td>pedal, electronic linkage, battery and/or capacitor, power converter, electric cable, suspension, hub mounted motors.</td>
<td>controller or pedal, wireless data feed and/or power/signal bus, battery and/or capacitor, suspension, electric drive motor, wheel</td>
</tr>
<tr>
<td><strong>Steering</strong></td>
<td>steering wheel, steering column, Mechanical / electronic / hydraulic amplification and assist, steering, linkage, suspension, wheel hub</td>
<td>steering wheel, steering column, mechanical /electronic/hydraulic amplification and assist, steering linkage, suspension, wheel hub</td>
<td>controller or wheel, wireless data feed and/or power/signal bus, battery and/or capacitor, suspension, electric steering motor, wheel</td>
</tr>
<tr>
<td><strong>Braking</strong></td>
<td>pedal, mechanical linkage to master cylinder, brake booster, hydraulic brakelines, suspension, brake calipers, brake discs, wheel hub, wheel</td>
<td>pedal, electronic linkage, suspension, electric brake, wheel hub, wheel, motors, electrical cable, battery/capacitor</td>
<td>controller or pedal, wireless data feed and/or power/signal bus, suspension, electric drive motor, wheel, and/or electric brake, battery and/or capacitor.</td>
</tr>
</tbody>
</table>

Table 1: Component Breakdown of Traditional Car, Electric Car, and Wheel Robot Car

In table 1, items listed before “suspension” are connected or part of the unibody/chassis. Items listed after “suspension” are in the domain of the wheel. Table 2 lists the items accordingly. It has to be noted that in conventional cars, only the wheels themselves, and not the hubs, brake discs, etc., are easily removed and swapped. In the Wheel Robot architecture, all items listed after “suspension” form one unit that is easily swapped.
Table 2: Components: Body Domain vs. Wheel Domain

<table>
<thead>
<tr>
<th>Domain</th>
<th>Traditional Car</th>
<th>Electric Car</th>
<th>Wheel Robot Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body</td>
<td>steering wheel, steering column, mechanical / electronic / hydraulic amplification and assist, steering linkage, pedal, mechanical/electronic linkage to throttle, intake system, fuel tank, fuel lines, engine, exhaust system, transmission, differentials, drive shafts, pedal, mechanical linkage to master cylinder, brake booster, hydraulic brake lines</td>
<td>Pedal, electronic linkage, battery and/or capacitor, power converter, electric cable, pedal, mechanical linkage to master cylinder, brake booster, hydraulic brake lines, steering wheel, steering column, mechanical/electronic/hydraulic amplification and assist, steering linkage</td>
<td>controller or pedal, wireless data feed and/or power/signal bus, battery and/or capacitor</td>
</tr>
<tr>
<td>Wheel</td>
<td>Wheel hub, brake calipers, brake discs, and wheel</td>
<td>Hub mounted motors, brake calipers, brake discs, wheel hub, wheel</td>
<td>electric drive motor, springing, and damping, and/or electric brake, electric steering motor, wheel</td>
</tr>
</tbody>
</table>

Below we discuss the tradeoffs arising from this comparison.

6.1 Wheel vs. Body

A traditional car resorts to a high number of components scattered throughout the vehicle body. The Wheel Robot architecture places more drivetrain components in the vicinity of the wheel. Perhaps the occupied volume and the complexity of the Wheel Robot increases, but other areas of the vehicle shrink. The challenges of integrating additional components like brakes and steering motors places more emphasis on standardization of connections both physical and digital.

6.2 Modular vs. Integrated

Traditional vehicle architectures have the benefit of an evolutionary past and incremental improvements based on the principles of lean manufacturing. Integrated solutions once proven have long shelf lives and can continue to improve, but take tremendous research and development times. The traditional architecture prohibits dramatic design changes and a new platform must be created for each vehicle type. Modular solutions can suffer from over engineering of components that must accommodate a large range of loading conditions. Therefore efficiencies in weight or excessive structure can begin to propagate in the system. This can be mitigated by producing a family of modular solutions, but it is inherit when producing more flexible and adaptable modules.

Wheel Robot architecture is not a fully modular solution like office cubicles or Legos, but a move
toward a more open source attitude towards design and user needs. Baldwin and Clark's analysis of the computer industry shows that innovation when done in incremental chunks like product modules allows further innovation at all levels of the product tree. They write:

*Because of the severe constraints it imposes, full-fledged modularity is never easy to achieve in practice. However, when implemented faithfully, modularity greatly reduces the costs of experimenting with new designs. With modularity enforced, it is possible to change the pieces of a system without redoing the whole. Designs become flexible and capable of evolving at the module level. This in turn creates new options for designers, and corresponding opportunities for innovation and competition in the realm of module designs.*

Wheel Robots open the possibility of reconfiguration as well as innovation by the manufacturer and end-user. The manufacturers can improve Wheel Robots by integrating new performance improvements to the wheels like better electric motors or more intelligent braking and suspension systems. The bodies can continue to develop more user centric properties that can be based on ergonomics and new material innovations. Users can continue in the tradition of modifying electronics, performance add-ons, body panels, and other cosmetic additions, but now with greater freedom to innovate and create forums that lead to end-user innovation.

### 6.3 Life Cycle: Short vs. Long

The product life cycle of typical automotive platforms is 5-7 years, although through lean manufacturing many Japanese manufacturers have been able to reduce this to 3-5 years. Cosmetic upgrades every two years have been offered by manufacturers to particular vehicle lines which offer limited stylistic changes and some novel user features. The benefit of such long life cycles is product stability and user familiarity. Unfortunately, innovation becomes prohibitively costly in such integrated solutions. In contrast, the consumer electronics industry has much faster product lifecycles because of reduced scale and complexity. The integration of on-board vehicle electronics and consumer electronics like cell phones and PDAs pose a great challenge due to the discrepancies in life cycles. Short term product life cycles can be enabled by investing in a modular system in which parallel developments can be achieved independently. A highly personalized passenger environment that accepts the inevitable variety in consumer needs can develop over time into new models of ownership which embrace short term passenger cabins and longer term Wheel Robots. Body geometries can be modified to create new forms, driving enthusiasts can tune their Wheel Robots for differing road conditions, and families can configure the vehicles to fit children’s needs. The OScar project is one of the first open source vehicle sites that promote user innovation.[http://www.theoscarproject.org/index.php]

### 6.4 Performance Measures

The architecture of the Wheel Robots in comparison to traditional car layouts dramatically changes performance measures. Steering, acceleration, and braking are digitally controlled thus making them programmable and adaptable to driver preferences. Wheel Robots are designed to reduce unsprung and rotational masses because the electric motors are not mounted on the hubs of the wheels, but in
their immediate vicinity. Batteries can now be placed freely in areas displaced by the removal of the main engine compartment, thus allowing for the flexibility to create the desired dynamics. Weight at the corners allows for better road contact patch distribution, but cornering stability is lessened due to momentum developed at each corner. The center of gravity of the Wheel Robot vehicle is potentially lower because of the concentration of components in the space of the wheel hub. The overall tradeoffs point to more customizable driving dynamics and freedom to place components in new areas that are potentially beneficial to vehicle performance and packaging.

6.5 Reducing cost and complexity:

Platforms, which contain the attachment points for drivetrain components present a great investment for car makers, thus the extensive use of platform sharing. The high cost of platforms arises to a large degree from their complexity, since literally hundreds of fittings for drivetrain components have to be integrated with crash structures while leaving enough room for passengers and cargo. Our Wheel Robot architecture greatly simplifies the platform structure, since the number of attachment points is reduced to a few.

Reducing costs and facilitating production of car bodies reduces the numbers that have to be produced in order to make a profit, which in turn allows manufacturers to produce a greater variety of vehicles at lower cost. Bodies with simpler shapes also lend themselves to production with simpler, more cost-effective methods. Due to their relatively compact dimensions and weight, the Wheel Robots can be transported cheaply and easily to production or sales locations of the Wheel Robot car. Separate production and distribution networks are also possible.

Table 3, summarizes the differences between the Wheel Robot architecture and the Traditional car architecture.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Wheel Robot car architecture</th>
<th>Traditional car architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>Fewer, compact, integrated</td>
<td>More, Distributed</td>
</tr>
<tr>
<td>Open Source</td>
<td>Allowed</td>
<td>Modifications only</td>
</tr>
<tr>
<td>Standardization</td>
<td>High</td>
<td>Only within the platform</td>
</tr>
<tr>
<td>Connections</td>
<td>Few</td>
<td>Many</td>
</tr>
<tr>
<td>Intelligence</td>
<td>Distributed</td>
<td>Integrated</td>
</tr>
<tr>
<td>Adaptability</td>
<td>Simple, inherent</td>
<td>Distributed, Limited</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Non-disruptive, swappable</td>
<td>Disruptive, complex, involved</td>
</tr>
<tr>
<td>Manufacture</td>
<td>Integration sites distributed</td>
<td>Distributed then integrated</td>
</tr>
<tr>
<td>Product Life Cycle</td>
<td>Short and long term</td>
<td>Long term</td>
</tr>
<tr>
<td>User Life Cycle</td>
<td>Separate, independent</td>
<td>Non-separable, dependent</td>
</tr>
<tr>
<td>Customizability</td>
<td>High, electronic, mechanical</td>
<td>Low, electronic, mechanical</td>
</tr>
<tr>
<td>Structural Integrity</td>
<td>Few key connection points</td>
<td>Integrated, many connections</td>
</tr>
<tr>
<td>Ride Comfort</td>
<td>Customizable</td>
<td>Tuned</td>
</tr>
<tr>
<td>Unsprung Mass</td>
<td>Comparable or less</td>
<td>Standard</td>
</tr>
</tbody>
</table>
### Table 3: Wheel Robot and Traditional Car Architecture Comparison Table

<table>
<thead>
<tr>
<th>Rotational Mass</th>
<th>Comparable or less</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>Mass Customized</td>
<td>Mass Produced</td>
</tr>
</tbody>
</table>

### 7 Conclusion

The transition from a craft-based economy of the late 19th century to industrialized and mass production economies left carriage and coach building as a relic of the past. Coach builders, artisans, and blacksmiths formed an economy of custom-made carriage bodies whereby customers would purchase components to be assembled by a master integrator. These highly personalized designs were a result of highly skilled local labor and regional materials and customs. The emergence of the industrial revolution created economies of scale that accelerated the development of products for the masses. Today, with new technological conditions that promote the free flow of information and the development of new fabrication and material technologies we can imagine the 21st century coachbuilder. New supply chains that promote just in time manufacture, and use of CAD/CAM technologies are now capable of rapid manufacture of one-off or limited production runs. Additionally, customer configurators allow manufacturers to develop a healthy picture of consumer needs and desires.

The Radical Re-modularization of mature complex products following the principles of modularity, open source architecture, and high levels of customization opens new design opportunities and product solutions. The fashion industry has already entered this evolutionary path. The current automotive paradigm requires the purchase of new vehicles from a manufacturer that provides some basic cosmetic and electronic customization options. This is similar to purchasing a suit from a department store and being able to select a shirt and tie to match your outfit. The difference lies in the fact that a consumer can easily purchase a pair of jeans and wear just the suit jacket to create a new outfit. It would be cost prohibitive to purchase a car and replace the entire interior with your favorite plaid shirt color. Given this analogy, a car is only purchased as a complete suit. No mixing and matching is possible. With a Wheel Robot architecture in place, this model of purchase and personalization shifts towards a customer-centric and innovation friendly environment. The 21st century coachbuilder is the first manufacturer to full deploy a flexible, adaptable, modular drivetrain elements and a completely personalized passenger cabin and exterior.

### 8 Acknowledgements

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9 References and Notes


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6. Chin, Ryan C.C., p. 3.

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