Product Grammar: Constructing and Mapping Solution spaces

By

Ryan C.C. Chin

Master of Architecture
MIT, 2000

Bachelor of Science in Architecture & Bachelor of Civil Engineering
The Catholic University of America, 1997

SUBMITTED TO THE PROGRAM IN MEDIA ARTS AND SCIENCES, SCHOOL OF ARCHITECTURE AND PLANNING, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

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ABSTRACT

Developing a design methodology that accounts for system- and component-level parameters in the design of products is a challenge for design and manufacturing organizations. Designed products like automobiles, personal electronics, mass-customized homes, and apparel follow design processes that have evolved over time into compartmentalized approaches toward design synthesis. Many products are designed "by committee" because the nature of the problem is sufficiently sophisticated that isolating the different disciplines of engineering, design, manufacturing, and marketing has become the only way to produce a product.

This thesis rethinks design methods by critically analyzing design rules and their role in product development. Systematic and unbiased mapping of possible configurations is a method employed in generative design systems. A mapping of a solution space is achieved by parameterizing the constraints of the problem in order to develop a feasible envelope of possibilities at the component and system level. Once parametric modeling begins, then a flexible hierarchical and associative assembly must be put in place to integrate components into the product structure. What results is a complex tree structure of the possible solutions that can be optimized to ergonomic, structural, aerodynamic, manufacturing and material perspectives. The tree structure is organized so that any changes in the component structure can be accommodated at any level. Subsystems can then be easily substituted in order to fit to mass-customization preferences.

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ACKNOWLEDGEMENTS

The story of this thesis began even before I could imagine that just one master's thesis was an adequate education from MIT. In early 1999, the Media Lab had just initiated a new special interest group focusing on cars called CC++: the Car Consortium. Betty Lou McClanahan was the coordinator for the program and, at that time, she was recruiting graduate students interested in automobile design. I had no expertise in this area, but had just received two travel scholarships to research the design and manufacture of automobiles in Europe, so I gave her a call. What would happen in the next 5 years with her help, and with that of many others, would seem unfathomable at the time and still remains so to me. First, I was able to shape that research done with CC++ into my Master of Architecture thesis on comparative design practices in the automotive and architectural industries. Then I was able to channel this new interdisciplinary approach towards research into a design goal that continues to generate new research paths and design possibilities.

I offer a tremendous amount of gratitude to what I call the "design triumphant" in Bill Mitchell, Frank O. Gehry, and Jim Glymph. Both Jim and Bill played a role in 1999 to challenge and to push the possibilities of this new research direction which has grown into something that has, irrevocably, begun to play a role in their professional and personal lives. Without their guidance, this project and its related academic endeavors would never have happened. Frank Gehry's progressive and uncompromising stance towards design inquiry and the use of technology in design sets the standard in modern design practice today. My relationship with Frank has allowed me to work with many individuals, both directly and indirectly through the Gehry office, and this has helped shaped this work.

Our collaborators at General Motors have helped turn a simple suggestion into an exciting proposition with the support necessary to make this happen. Thus, I would like to warmly thank Gary Cowger, Wayne Cherry, and Frank Saucedo for their patience and willingness to work with the MIT Media Lab and to reduce the gap between academia and industry.

It has been a pleasure to work with the many talented individuals in the design workshop courses. Let me mention a few in particular that have greatly affected this work. The super-talents and immeasurable time and caring that Axel Kilian has bestowed on this project continues to astonish me, and without him this project would not have progressed this far. Franco Vairani, throughout this project, has provided the pragmatism and wisdom to forge ahead with the work. For this, I am grateful. Finally, I would like to thank Will Lark, Phil Liang, Patrik Künzler, Raul-David "Retro" Poblano, and Mitchell Joachim for their participation in the workshops. They have powerfully shaped the outcomes of this project and I have learned so much from these talented individuals. Their camaraderie, expressiveness, and friendship along the way has made this research so fulfilling.

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PART I. THE DESIGN STUDIO

1. INTRODUCTION

This thesis research parallels the design and research work for the MIT Media Laboratory's Concept Car Project. The project is a collaboration between the Los Angeles-based architect Frank O. Gehry, General Motors, and the MIT Media Laboratory and it explores new design processes (Gehry/MIT) as applied to automotive design. The vehicle serves as a platform for Media Lab technological innovation and investigates issues of connectivity, mass-customization, human-machine interface, manufacturing, and design computation. General Motors will provide engineering and design support and fabricate the show car. Expected completion date of the concept car is 2006.

In the fall semester of 2003, under the direction of Professor, William J. Mitchell, and the MIT Media Lab established two workshops to explore the design of the concept car. Each course would spend an entire semester (approx. 14 weeks) to tackling the problem of reinventing the automobile. The fall class, MAS966 Design Workshop: Concept Car with GM and Frank O. Gehry, was created to provide a convenient forum for students, professors, and sponsors to collaborate together. Our challenge was to rethink the automobile by asking fundamental (and often dumb) questions and then, to suggest solutions to those questions. This course was intended to allow experts to offer their knowledge about a particular area pertaining to the design and manufacture of automobiles.

Once we established the baseline knowledge of many automotive issues and systems, smaller research groups, composed of the students, developed their own positions about the automobile of the future. These groups focused on specific areas like interiors, powertrain, and vehicle control. Later in the semester, the groups were reconstituted to form synthesis teams that had student experts in each area resulting in a broad coverage of topics before the final synthesis of vehicle concepts. Several intense design charettes involving outside participants from sponsors and collaborators were strategically scheduled throughout the semesters to provide meeting points and working sessions at MIT.

My role as studio coordinator was to prepare the course, coordinate the collaboration, manage the day-to-day student learning activity and to provide senior student level guidance in the design research. Many of the themes in this thesis were explored both prior and during the courses in collaboration with professors, researchers, students, and sponsors. I will refer to this work throughout the next several chapters.

The development of a sophisticated and flexible product grammar for design begins with a careful study of the major systems and subsystems that compose any product. The study includes the relationship of parts to the whole system, the role and functionality of each system and component, manufacturing and engineering constraints, etc. It also allows us to identify the new design opportunities that arise from re-questioning the synthesis of these parts. During the past year, both design workshops MAS966 (Fall, 2003) and MAS968 (Spring, 2004) have focused simultaneously on components and total vehicle concepts, as this best mimics a product development and design process promoted by the Gehry office and Media Lab.

2. THE DESIGN WORKSHOP

This section describes the major research areas that were investigated. These eventually led to establishing a new high-level architecture for the vehicle design. The key to the project and the design workshop was the nature of the collaboration. The interdisciplinary make-up and working methods of the Media Lab were imitated during the design team assembly. Students and collaborators gathered from Architecture, Industrial design, Mechanical Engineering, Sloan Automotive Lab, Computer Science and Electrical Engineering, Aeronautics and Astronautics, and even Neuroscience. We set out to establish a design studio space where work could take place, and then be reviewed and displayed for others to see and to critique. During this time, the project called for the establishment of a satellite studio at the Gehry offices as another base of operations to initiate design inquiry with our collaborators.

A. The Design Studio at the MIT Media Laboratory

We began with six research groups as the semester started. By investigating existing typologies and classification systems typical of the current design and research groups in industry we were able to understand past innovations, why they were successful and how they failed or even came into existence. These groups continued research on their topics throughout the semester, with occasional time periods where the focus shifted to synthesis of ideas. These groups are listed below.

1. Interior

The study of ergonomics has shifted from the goal of maximizing operator productivity while minimizing fatigue and discomfort to the study of all human factors related to natural and artificial environments. The interior group focused on the influence of ergonomics on interior envelope, cone of vision, seat configurations, and their architectural configurations to the outer envelope and structure. It also looked at vehicle control constraints for the design of the driver interface. Several of these areas can easily be parametrically defined and built three-dimensionally. Many factors can be expressed parametrically. These include reach distances given a particular hip point, or all the minimum and maximum angles and distances given a person's stature and sex. This research will be described further below in the "parametric design" section of this thesis.

Another key area of the interior group was the definition of solution spaces. Solution spaces are mappings of the possible configurations to a chosen aspect of a problem. In the case of the interior group, this meant defining the possible seating configurations. The key to the solution space is to produce an unbiased map whereby all branches of the solution space are allowed to fully form. I will illustrate the role of solution spaces in the product grammar hierarchy in the section called "solution spaces."

2. Envelope

The research group began by looking at existing envelope conditions on traditional vehicles. Body panels, doors, windows, lights, mirrors, and grilles were starting points for our investigations. The question of an outer protective skin that "encased" the major systems and subsystems became the driving theme behind the organization of the explorations. The first investigation was to create a parametrically defined surface that would represent the outer envelope (see Figure I-1). Changing dimensional constraints such as wheelbase, overall length, ride heights, window line, roof height, etc can parametrically modify this surface.

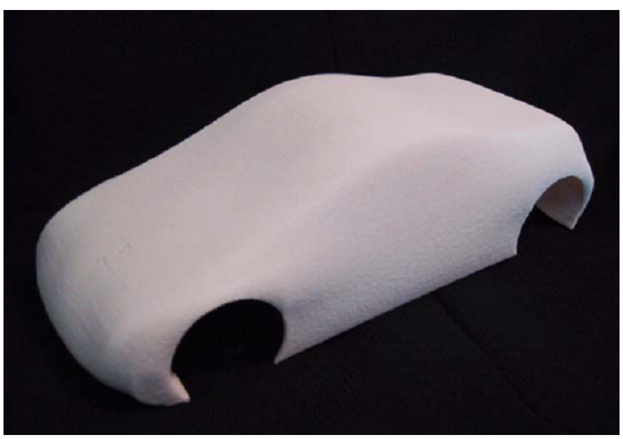


Figure I-1: 3D print of parametric envelope study

Listed below are the themes that the team tried to address:

Opacity/transparency: Can we describe and define areas of the exterior envelope?

Continuity/discontinuity: How do we define and address the surface quality of the exterior envelope? How do we formulaically accept discontinuities in the envelope such as elements like grilles, window openings, signage, etc?

Subdivision: How do we divide the surface of the envelope to allow for manufacture, window openings, or allow for gradation or flexibility in texture or grain?

3. Chassis-Structure

Initial research began with precedent studies of existing chassis types like the ladder, frame, tubular, monocoque, semi-monocoque, and uni-body. The goal of this group is to define flexible, modular, strong, and light structural systems that could accommodate our design goals. Several 3D models were created to explore these ideas, such as the modular frame chassis, railcar (see Figure I-2), egg car, and expandable chassis. In CATIA we are able to run structural finite element analysis to optimize these structural systems. Parametric constraints are built into the models for dimensional stability.

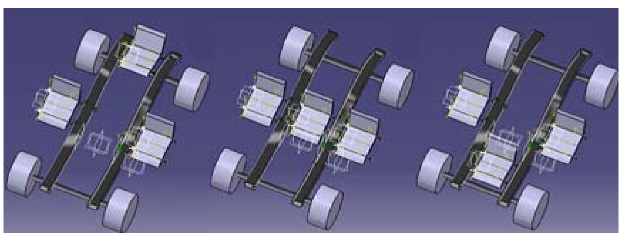


Figure I-2: 3D parametric CATIA model of Railcar design

4. Powertrain

Several powertrain platforms were under consideration in this research group. GM asked us to consider the fuel cell platform in the form of the Autonomy and Hywire concept vehicles. We also sought the help of Prof. John Heywood, Director of the Sloan Automotive Lab for a broad survey of automotive propulsion systems, their benefits and disadvantages, and their responsiveness in providing a completely sustainable energy cycle. The study included traditional internal combustion engines, hybrid, and fuel cell systems. To better understand the complexities of powertrain systems and their impact on design, we divided the task into several categories. In this process we began the building of parametric models which reflect particular themes:

A. Fuel economy optimization

Depending on the powertrain selected, the study of fuel economy becomes more or less complex. For example, hybrid systems have two major components: a gasoline engine and an electric motor. The use of these components in combination with proper aerodynamics and weight distribution determines fuel efficiency. Hybrid systems have the benefit of regenerative braking thus dramatically improving the overall energy cycle. Electric motors can be used during low speed (traffic jam conditions), and the gas engine can aid the electric motor at higher speeds. The gasoline engine aids the charging of the battery that runs the electric motor.

B. Weight distribution/spatial configuration

The building of powertrain components was determined by creating target volumes depending on the range (200 miles), efficiency, etc., therefore leading us to another design table that was used to input component dimensions and weights. The parametric model allows for the designer to quickly recalculate different configurations and optimize for weight distribution, center of gravity, and other crucial dynamic outputs. The model below built by Phil Liang illustrates the design table inputs which are tabulated and applied to the 3D model. Any changes in the design table are reflected and evident in the 3D Model.

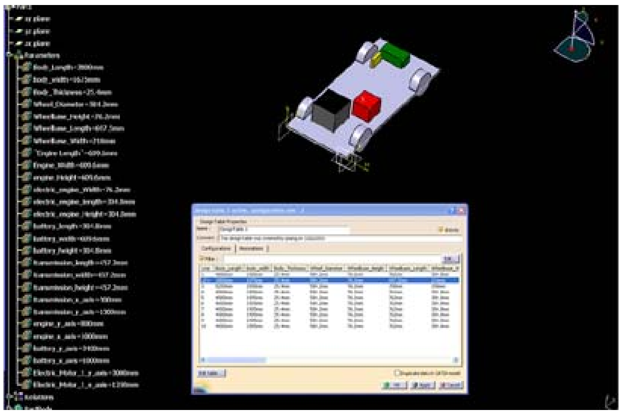


Figure I-3: Catia Design table

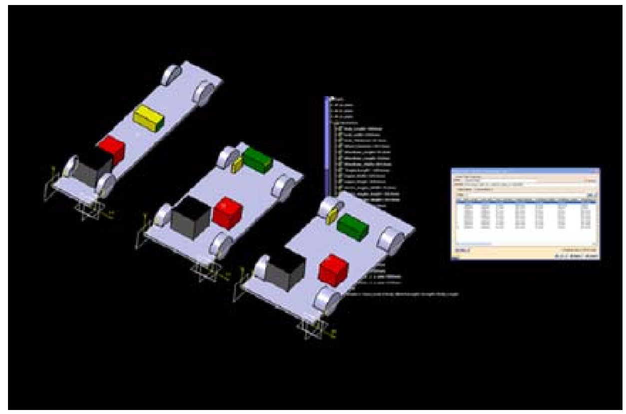


Figure I-4: Parametric variation of powertrain system

C. Optimization

A number of propulsion systems were under consideration. Both hybrid and fuel cell systems can be described by a set of design rules in a parametric manner. David Gerber explored the fuel cell platform motivated by General Motors' offer of the Autonomy platform as a possible chassis candidate. His investigation was to think of alternative configurations of the fuel cell platform. His model can be optimized for fuel cell size, weight distribution, wheel base dimension changes, and the number of passengers.

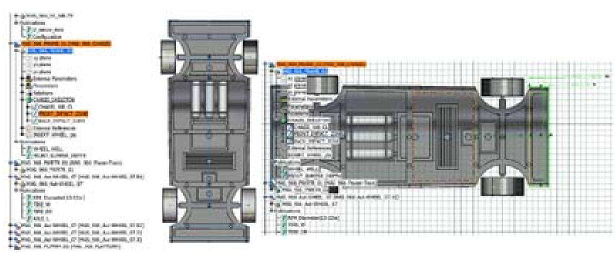


Figure I-5: Design table implementation for Autonomy

Figure I-6: Autonomy CATIA 3D model

5. Vehicle Control

The design of the vehicle interface took form from the vehicle context. We began to investigate the relationship between the car and the city. The vehicle control group mapped the inputs to the driver such

as audio, visual cues, haptic information about the road, city-pertinent information, etc.
Chad Dyner, Anmol Modan and Jonathan Gips produced a driver centric diagram (Figure I-7), which maps out not only typical inputs like speed, fuel consumption, and radio station, but also the car's context including city information, GPS data, and other tangible information envelopes.

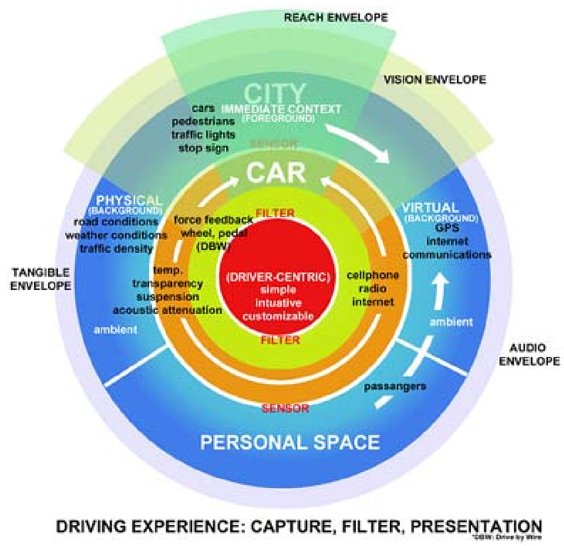


Figure I-7: Driver input diagram

6. Materials

A broad spectrum of new and conventional materials was investigated very early in the process. Some key material characteristics included lightness, strength, recycle-ability and durability. The Materials group became the key player during the synthesis stages as their research influenced every other research group.

B. The Satellite Studio and Emergent topics:

During the fall semester we established a satellite studio at the Gehry design offices. The goal was to engage the office in design studies, to create a transfer point to funnel ideas from MIT to Los Angeles, and to begin a parallel design effort. It was paramount to have a place of reference for Frank Gehry and his design team to interface with us on an everyday basis. Axel Kilian was our representative at the Gehry office. Along with the above-mentioned topics, design activity in the Gehry office offered us the opportunity to research areas of personal interest in addition to those already selected.

A critical part of the Gehry design process is the interplay between physical and digital models. Physical models are intrinsically part of their process of making; therefore they place emphasis on their production. The first task was to take the seating configurations and to build representative models using wooden blocks (Figure I-8). The blocks represent a parametric volume which corresponds with a person's seating volume. Volumes would be added together, in addition to wheels and representative mechanical components, in order to create an assembly. During the visit a CATIA model was made in parallel to simulate the same configurations and also include other factors such as line of sight, the beginnings of dimensional accuracy, engine component volumes, etc.

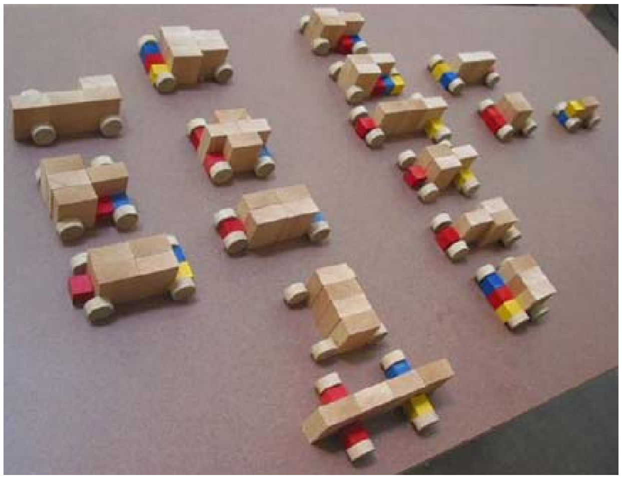


Figure I-8: Wooden block study models

Early in the architectural design process, the Gehry office produces programmatic study models represented by colored blocks. The programmatic study blocks represent volumes of space that correspond to spaces established by the building program. Established within that model are service spaces, lobbies, vertical and horizontal circulation, office spaces, and other elements. The early models enable the study of adjacencies and spatial relations, with a number of design rules. Some design rules may be as simple as “the kitchen should be relatively close to the garage” or “a hallway may not be longer than 50 feet without an exit.” Some rules reflect zoning or building codes, while others may be constructed for lighting, acoustic or structural reasons. The benefit of building models is the speed with which the models can be manipulated to create many early design options. The tangible nature of building physical models informed the design process, but building a 3D model with either parametric or generative properties can complement the physical models. The building of wooden block models for the concept car is an analog to the architectural program blocks. The Gehry office, along with Axel Kilian, built a number of models that represented all possible interior configurations. This process, called “mapping the solution space” is discussed in section D under “Research Themes.”

The models prove to be helpful in identifying innovative and interesting configurations. Some innovations forced us to question fundamental assumptions. For example, the diamond or "rock band" (single passenger in front flanked by two side passengers, followed by a fourth seat) configuration provides for many benefits such as maximum seating volume ratio to overall size, good vehicle dynamics, and a small wheel base for our urban site. Assuming drive-by-wire as the driver interface, such a configuration works because configurations of 3 still allow for the front passengers to sit parallel to each other while the front seat is used for storage. Cultural and social norms that usually block innovations like this are enabled by first allowing an unbiased methodical mapping of solutions. Another positive effect from the simple mapping of solution spaces is emergent innovation areas. Once a mapping is presented, such as the seating configuration, we can then introduce a number of optimization themes or filters. Let us examine two topics that were investigated after the interior mapping. We begin by asking several top-level questions with regards to these topics:

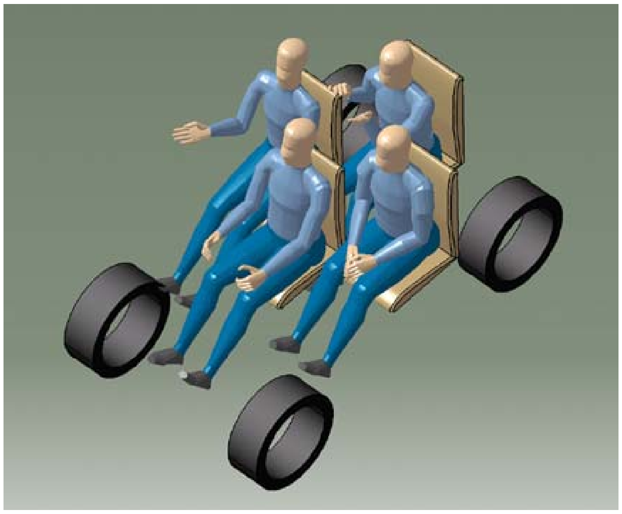


Figure I-9: "Rock band" seating configuration

1. Powertrain:
Will this configuration work from a vehicle dynamics standpoint? If so what opportunities are generated from this assumption?
How will this affect the spatial qualities of the interior and the overall form of the exterior?

2. Ingress/Egress:
How easy or ergonomically comfortable is it to access the seating?
If so, does this allow for highly engineered standard door systems or will it require a new door design?

3D parametric models are used to optimize specific areas in question such as weight distribution, center of gravity, and other crucial vehicle dynamics parameters. Building a layered model that includes spatial configurations and powertrain configurations allows us to study the interplay between these pieces. In the case of the "rock band" configuration, vehicle dynamics are very good because of equal weight distribution and spatial layout. The diamond layout provides an excellent interior volume ratio, but the configuration needs to be studied further to judge its impact on aerodynamics and the exterior form.

The front and back seat poses the biggest challenge for the design of the door system. The doors need to allow for easy access to the center section of the interior, yet also allow those sitting in the interior to control the opening and closing of the door. Such paths allow for innovation because hierarchical decisions determine the order of design problem solving. Creating flexible hierarchies in the development of product grammars allows the designers to quickly change order. These yield many design iterations without sacrificing time to create additional rules.

3. RESEARCH THEMES

A. Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) and Rapid prototyping

The use of Computer Aided Design systems has evolved in different industries in many different ways. The building industry used systems like AutoCAD throughout the 1980s and 1990s as an automated drafting system for the production of construction drawing sets. The drawing sets were used to define the design through 2-dimensional orthographic projections. Designs were illustrated through the traditional plan, section, and elevation points of view. Perspective and other 3D representations were only references to the 2D drawings. Construction documents detailed the design to the architect, engineers, and contractors so they could produce the necessary designs, budgets, and calculations for construction. Only recently, in the last 10-15 years, has the building industry utilized the full capabilities of sophisticated and modern CAD/CAM systems.

The automotive industry has had a long-standing relationship with CAD systems. CAD systems are used heavily for every stage of the product development process.

1. Concepts - software programs like Alias Wavefront are used in combination with CATIA for the early stages of design.
2. Development - programs that complement the use of CATIA, Pro-Engineer
3. Manufacturing – CATIA, Solidworks

The aerospace industry has been the leader in the use of advanced CAD systems. CATIA is made by Dassault Systemes, originally a French aerospace company. CATIA was used widely in the design of the Boeing 777. It was the first instance where CAD was used during the entirety of the design development process.

CATIA has been an influential software package changing the way the automotive and aerospace industry designs and manufactures. It is slowly making an impact on the building industry and, in particular, in the Gehry design office. CATIA is the predominant CAD/CAM software used in the automotive industry. Because of this, and because of its use in the Gehry office, it is the most sensible choice for this project and thesis research.

Computer numerically controlled (CNC) machinery like mills, lathes, and cutting machines have been in use for decades. However, only in recent years have they become widely available through the advent of rapid prototyping machinery like 3D printers and laser cutters. Such machinery speeds up the design process because designers and engineers can quickly develop 3D models and produce mockups in a matter of hours instead of weeks. The Media Lab, and our collaborators, all use rapid prototyping machinery like the Fused Deposition Machine (plastic) and the Z-corps (plaster/starch) 3D printers and continued to utilize them for the concept car project. Laser cutters have also become more accessible to users and allow designers and engineers to quickly and precisely cut 2 Dimensional shapes using flat materials.

B. Parametric Design

Parametric design utilizes constrained inputs in a 3D environment. The goal of parametric design is to create 3D models that can vary in shape and form depending on a number of constraints that can be input into a CAD environment via numeric input or from a design table. By creating parametric models, designers and engineers can quickly generate designs, build design rules, add functional constraints, visualize the design, and test for manufacturing.

In the very early stages of the concept car project, the group researched simple components like the wheel. The wheel can be described very simply in geometric terms as a cylinder with a cylindrical volume removed from the center. This simple description can be built by describing the wheel as a given diameter, inner radius, and wheel depth. These values can be assigned or given as variables. Additionally, we can build relations between each of these variables, for example: the wheel depth is 1/2 the diameter of the wheel. Once we have described the wheel in these terms, we can quickly build an infinite number of variations of the wheel, effectively building a smart parametric model. As the wheel design becomes more complex with more and more variables, the design becomes more realistic. We can begin to assign other variables for the chamfering of the corners, describe dimensionally the relationship between the tire and the rim, the number of spokes in the hub, so that eventually we can accurately describe a wheel assembly. Once that assembly is in place, we can then apply design rules that govern the limits of the design. For example, a stability function can be built in as a constraint. The

3D model will not allow any designs that violate that constraint. Utilizing 3D printing technology we are able to produce physical scale models in quick fashion as evident in Figures I-10, 11.

Figure I-10: Z-Corp 3D print of parametric wheel

Figure I-11: FDM 3D print

Applying design constraints is an essential task of the designer/engineer using parametric design. Parametric design can also be used not only in generating and evaluating dynamic constraints, but also in creating dimensional/geometric constraints. Using the same wheel example again, the design can limit the size of the wheels to a set of known geometric constraints. The design calls for the use of conventional tires of known maximum and minimum sizes, so limiting the size of the wheels reduces the number of possible solutions in order for the design team to focus on other design features. Figure I-12 illustrates just a small sampling of the many designs possible.

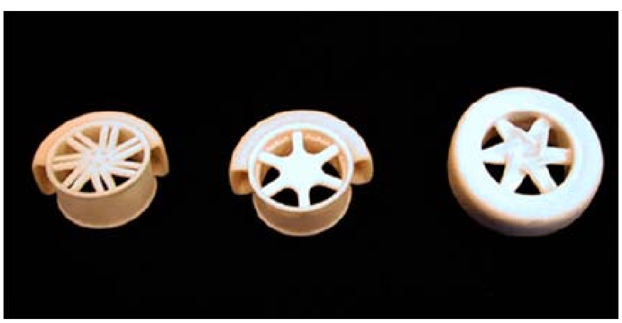


Figure I-12: 3D print parametric variations

Design tables are effective because by using a spreadsheet format, inputs can be organized so that the designer can make many changes and instantly see that result reflected in the model. One example that proved to be an effective use of the design table was the study of "powertrain" configurations implemented in MAS966. The problem was to investigate the different variations a powertrain can be configured. The powertrain in question was a hybrid system consisting of gasoline engine, electric motors, batteries, electro-mechanical/fluid conduit connections, and so on. The task was to build a parametric model that examines the redistribution of these components throughout the car in order to rethink the spatial and dynamic qualities of the overall design. We implemented a design table which considered the weight, geometry, length of connections, center of gravity, and associated ratios (i.e.

weight distribution) that generated new configurations instantly. By using design tables, the research team was able to examine different configurations of the components and to evaluate the balances between the constraints. In some designs, weight distribution was compromised to maximize spatial freedom whereas other designs allowed for good weight distribution and dynamic qualities, but dictated specific seating configurations for the interior. Building parametric studies of components allowed the design team to generate alternative solutions in an unbiased manner.

Parametric design is also useful in developing a number of solutions for a particular assembly problem. In the case of vehicle interiors, Will Lark investigated alternative designs by parametrically defining 3D models using ergonomic constraints. Figures I-13, 14 and 15 show different interior configurations based on typical ergonomic comfort levels for sport cars, sedans and sport utility vehicles. In this model, the designer can input a wide range of human dimensions, which factor into the model and yield a 3D design. Building parametric relationships between ride height, roofline, wheelbase, and cone of vision are all factors in this model. Figures I-16, 17 and 18 show how the model inputs (2D) are translated into a 3Dimensional model.

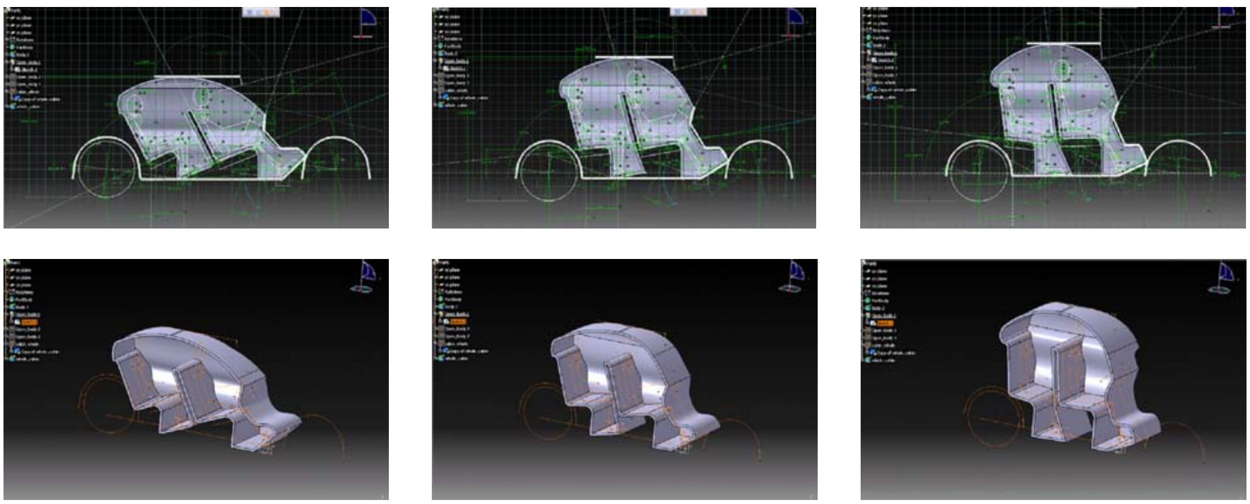


Figure I-13, 14, 15, 16, 17, 18: Parametrically defined interior ergonomic studies

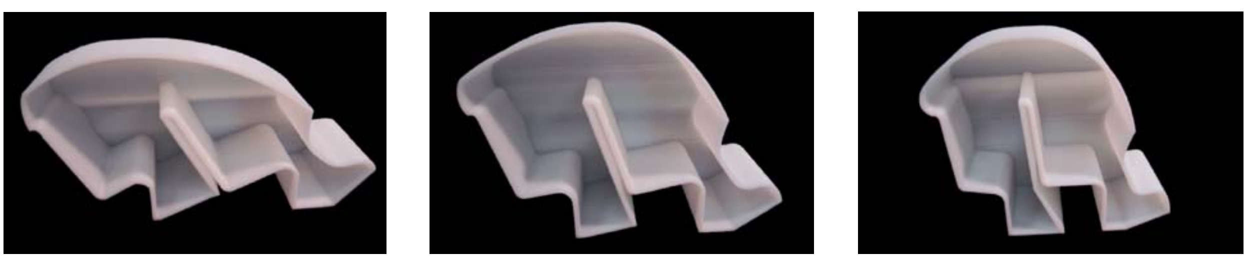


Figure I-19, 20, 21: FDM 3D prints of varying ergonomically defined interior studies

The 3D model is then translated into a usable file format for the 3D printer to produce models in Figure I-19, 20 and 21. This modeling process is helpful for designers and engineers to visualize different design configurations and to quickly change parameters thus accommodating differing design concerns. Rapid prototyping tools allow for abstraction because Figure I-22 shows an overlay of several ergonomic configurations in one 3D print model. The ergonomic interior envelope that accommodates all ergonomic conditions would outline the perimeter of this model.

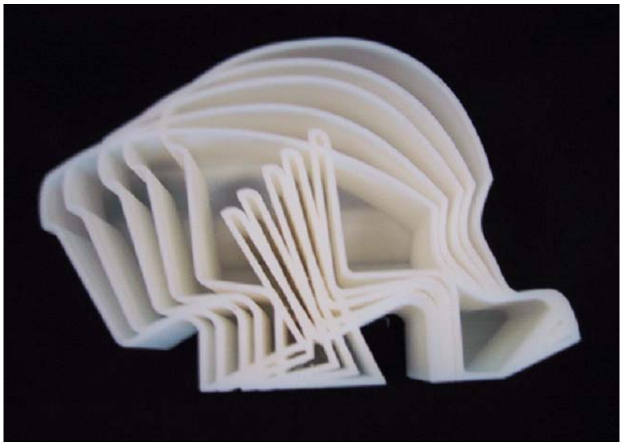


Figure I-22: 3D Print of composite overlay of ergonomic interior configurations

Constraint and geometric inputs can be built in, not only at the component level, but also at the assembly level. Many assemblies are bound by geometric constraints whereby avoiding clash conflict is crucial. In the case of architectural design, clash detection is critical in determining whether or not two subsystems like HVAC and structural systems will collide. In the automotive industry, connecting two or more components can be vitally important. Let us examine the wheel again to illustrate this point. Once we have defined the geometric and engineering constraints of the wheel component, we need to constrain the wheel assembly to the axle assembly. For instance, “the center of the wheel assembly shall be co-axial with the center point of the axle connection and the primary face of the wheel assembly shall be normal to the central axis of the axle.” This is a simple example, but in any product assembly there can be thousands of constraints of varying complexity. A sequence of components comprises an assembly. In our wheel example, the hub is connected to the axle, which is connected to a transmission, which is connected to a differential, which is connected to the motor. This sequence has many connections that are either mechanical or electrical. Parametric assemblies become important to the design team because parametric models that are built robustly eliminate the need to re-build entire 3D models in order to accommodate changes in the design. With a parametric model, the designer can quickly make design changes in, say, the wheel design and see how that would affect the wheel well geometry or the overall proportions of the vehicle. Figure I-23 shows a 3D model built by Will Lark and Victor Gane that combine the interior and exterior envelopes into one model assembly. This model allows the design team to understand the interaction of both assemblies as well as the remaining space left for mechanical components like suspensions, drive trains, conduits, etc.

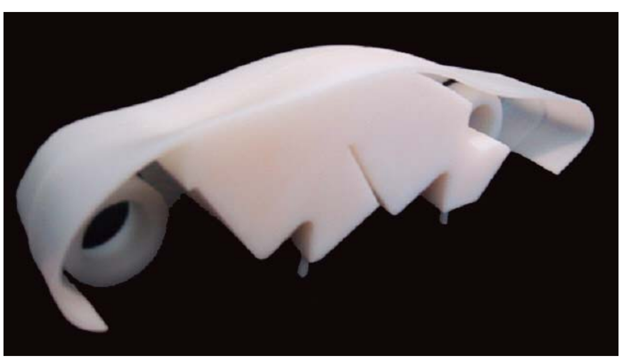


Figure I-23: 3D print combining interior and exterior envelops.

Models built in the workshop vary in complexity depending on the design issue in question and the number of constraints under consideration. One of the first studies done by Axel Kilian investigated seating configurations relative to wheelbase, cone of vision, and powertrain layout. His study in Figures I-24, 25, and 26 show a 3D parametric CATIA model that produces a variety of configurations based on the number of seats for passengers and seating position. The design team can rapidly study any seating configuration and begin to understand the effect it has on those issues.

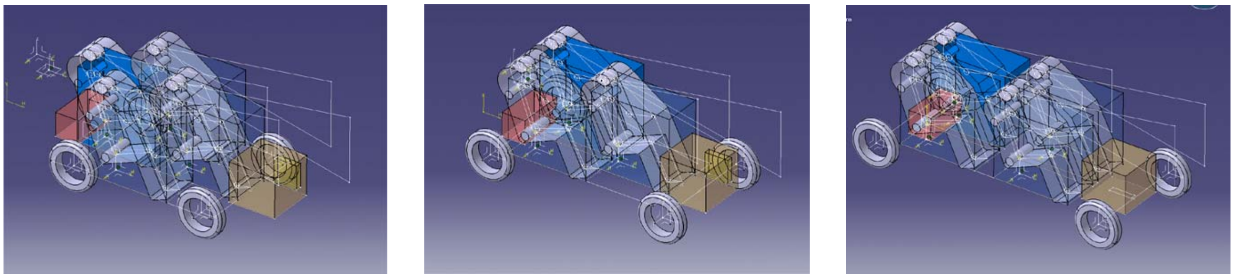


Figure I-24, 25, 26: 3D parametric seating model

Building design rules that are influenced by manufacturing constraints adds another level of sophistication to parametric design. Depending on the development stage, this is a valuable exercise in the product development process. Manufacturing constraints affect supply chain decisions, material selection, build/fabrication schedule, assembly, and even dictate formal and aesthetic choices. The academic and professional research of Dennis Shelden of Gehry Technologies and MIT is one example whereby parametric design and fabrication have meaningful confluence.

Shelden's doctoral dissertation called “Digital Surface Representation and Constructability of Gehry’s Architecture” proposes a structured and formulaic methodology for which complex algorithms implemented in CATIA are used to determine the manufacturability of the complex shapes and forms from the Frank O. Gehry Design office. Difficulties exist in fabricating such complex surfaces because:

1. Organization and tracking of components and individual elements
2. Limits of material choices
3. Connection points

Complex building forms such as Frank Gehry-designed buildings or automotive products require the tracking and organizing of tens of thousands of components and individual elements. This limitation has been challenged by technological improvements, especially in 3D modeling systems. Simply being able to track, locate and position the proper element at the proper angle and position has changed the way building practice is done. Components can be easily numbered, fabricated in a controlled environment, and properly managed, allowing for fabrication to run smoothly.

In the construction of the Experience Music Project (EMP) and other Gehry-designed buildings, CATIA was used to determine the degree of curvature for certain building elements. The degree of curvature was crucial in that, beyond a certain degree, building panels could no longer be produced with flat or ruled materials. They would have to be made with stamping or mold technology, driving costs beyond budget constraints. The manufacturing and design process intersected throughout the building process to ensure the feasibility of the design, yet also determine areas within the design where the fabricators would deviate from standard rule shaped fabrication and shift to mold technologies.

C. Mapping of Solution Spaces

A crucial step in the design process is the mapping of solution spaces. To illustrate this, let us use an example. Car interiors have been configured nearly in the same manner since the 1920s. They are usually set up with one driver either on the right or left side (depending on the country in which you are driving) and a passenger in the other. This configuration is the standard for sports cars, trucks and coupes. Another row of seats is added for sedans and SUVs. Single seat configurations were common for very early cars, but fell out of favor relative to those for two passengers. Breaking this tradition takes an unbiased mapping of solutions regardless of any deviations for social or cultural norms. The work of Axel Kilian best demonstrates how to map a solution space:

Step 1: Select a simple component that can be parametrically described. Figure I-27 shows a seat that can dimensionally vary based on human measurements.

Step 2: Combine components in all possible variants.

Step 3: Add additional components (wheels, powertrain, storage, etc) to build an assembly. Figure I-28 shows how a simple mapping can yield a wide variety of design solutions. A single passenger vehicle can be described as a recombination of the additive elements to a single passenger volume. This effectively separates vehicle form from vehicle typology, thus opening up abstraction techniques that inform the design process.

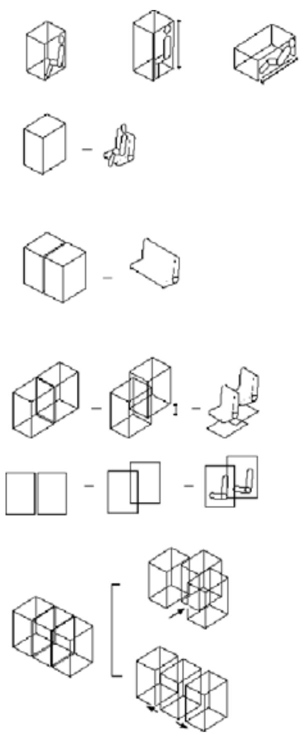


Figure I-27: Parametric seating modules

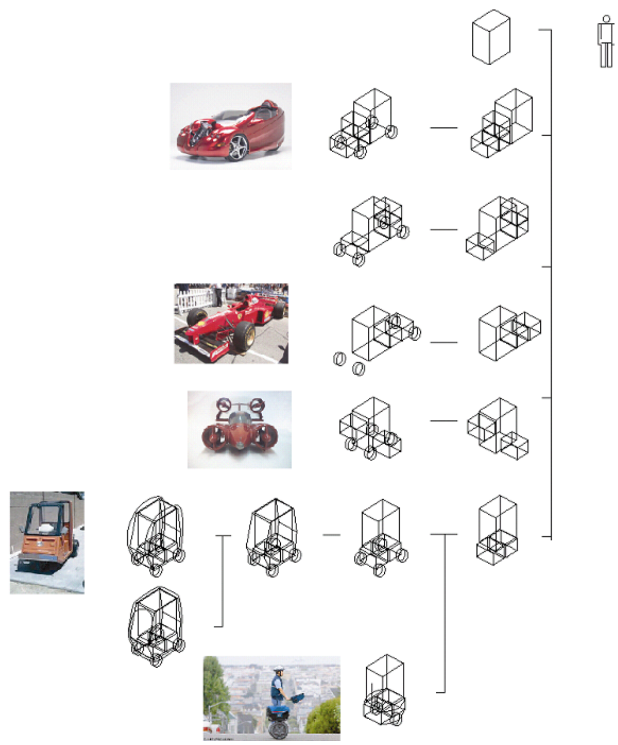


Figure I-28: Single passenger solution space

Step 4: Finish the building of the configuration by adding structure and enclosure. Figure I-29 shows how two completely different vehicles can be derived in this process by just one high-level design change.

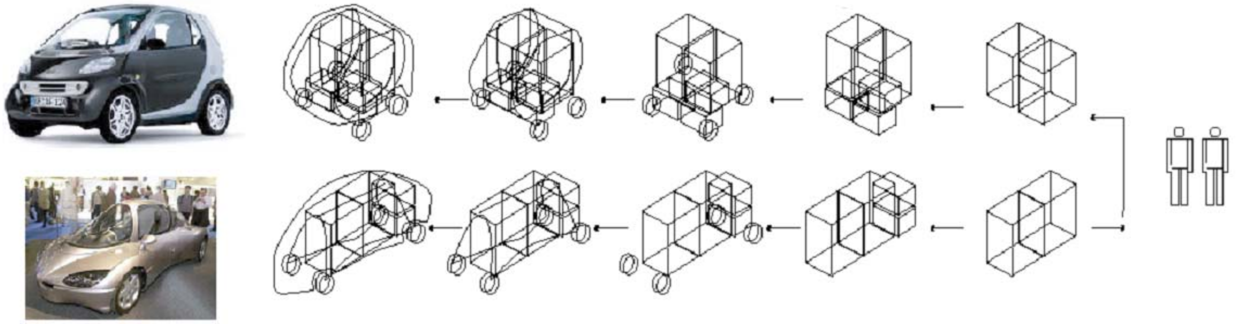


Figure I-29: Comparative derivation of car configuration

Step 5: Repeat mapping by adding passenger modules. Figure I-30 illustrates the whole spectrum of seating possibilities ranging from one to four passenger configurations.

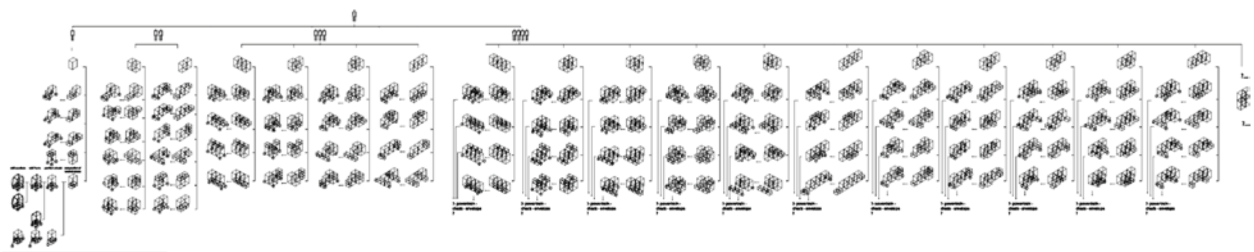


Figure I-30: Solution space map of seating configurations

A closer examination of the map provides allows the design team to investigate each configuration for other considerations. Figure I-29 shows a 3 + 1 configuration. This does not typically occur in conventional cars. Upon examination, this configuration would permit the rear wheels to be placed closer to the center of the cabin thus shortening the wheelbase of the vehicle. This is ideal for parking in the city, but a new door system will need to be considered. The mapping of solution spaces leads the design team down paths that normally would not be taken. Asymmetric designs considered unfeasible are brought back into design consideration. Given the natural problems of placing and balancing the weight distribution of powertrain components, asymmetric designs have large visual impact.

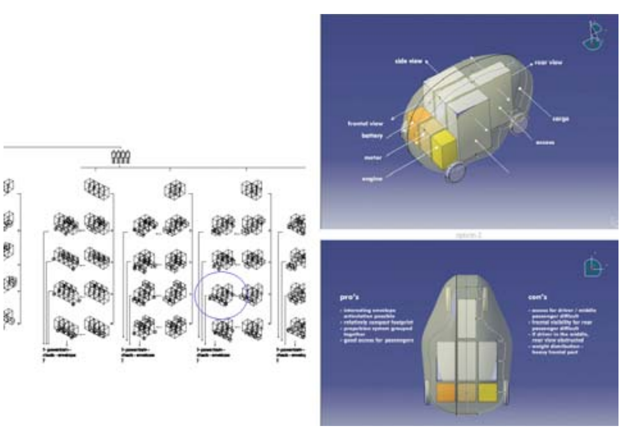


Figure I-31: Solutions space, 3+1 seating configuration

The mapping of solution spaces provides a systematic method of design generation and evaluation. They can be flexible enough to accommodate differing design issues. In the case of the passenger configuration map, the design team can begin the process by starting with the seating, then cross -filter the map by arranging powertrain components. Once those configurations are in place, and then parametric design tables can perform the optimization to refine each design.

PART II. GENERATIVE DESIGN SYSTEMS

This thesis focuses on the synthesis of parametric design, solution space mapping and generative design systems. A number of generative design systems were considered during this research including genetic algorithms, shape grammars, and invention systems. Genetic Algorithms (GA) have entered the design research space only recently, in the 1980s. They have been used in solving problems in the medical industry, but have begun to be seen as applicable to engineering problems like the design of optical structural configurations for trusses and beams. Although both GA and invention systems have been thoroughly researched, much more needs to be done before their successful application to product grammar development. The formalism of shape grammar research, however, has resonated with the research goals of the workshops and this thesis. Part II focuses on describing a number of shape grammar research examples that aid in the development of the product grammar.

SHAPE GRAMMARS

Developments in the study of shape grammars over the last 30 years inform the construction of the product grammar. Since their invention in 1972 by Stiny and Gips, shape grammars have been one of the key research areas in design and computation. A shape grammar is a set of shape rules that apply in a step-by-step way to generate a set, or language, of designs. Shape grammars are both descriptive and generative. The rules of a shape grammar generate or compute designs, and the rules themselves are descriptions of the forms of the generated designs[1] This being said, the creation of a product grammar at the level of complexity of an automobile depends on the number of design rules implemented into the grammar. An examination of the different types of grammars led us to investigate a variety of research topics: Frank Lloyd Wright Grammar (Koning, Eizenberg), Malagueira Housing Grammar - Alvaro Siza (J. Duarte), Coffeemaker Grammar (Cagan), Harley Davidson (Cagan), Buick Grammar (Cagan), BMW grammar (Soares), and the Beetle grammar (Arida).

1. The Coffee Maker Grammar

The beginnings of shape grammar research explored the application of generative systems to simple design problems. The first shape grammars looked at patterns in glass and in the design of patterns. Later grammars investigated their application to more complex design problems like Frank Lloyd Wright-designed Prairie homes. More recently, in 1998, Jonathan Cagan published "A Blend of Different Tastes: The Language of Coffee Makers," an article that described how shape grammars can be applied to the design of simple coffee brewing machines (Figure II-1).

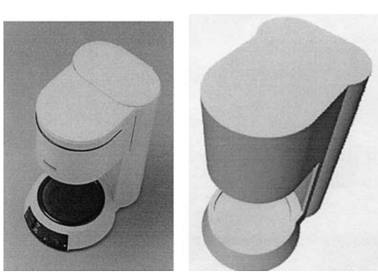


Figure II-1: Coffee Maker Grammar

[1] Knight T., http://www.mit.edu/%7Etknight/IJDC/frameset_introduction.htm

2. Malagueira Housing Grammar

The research work of José Duarte investigates the use of shape grammars in mass housing. His focus is the Malagueira housing complex designed by Portuguese architect, Alvaro Siza. The architect designed housing blocks using a set of simple rules for circulation, use of space, orientation, and the sequence of spaces. Siza's design intent was to create a flexible system of construction that could accommodate the different needs of the occupants. Duarte's work takes this set of rules and uses shape grammars to generate alternative designs. Figure II-2 shows the initial Siza designs that were considered during the research investigation. The original prototypes became the basis for the generating the design rules for the grammar.

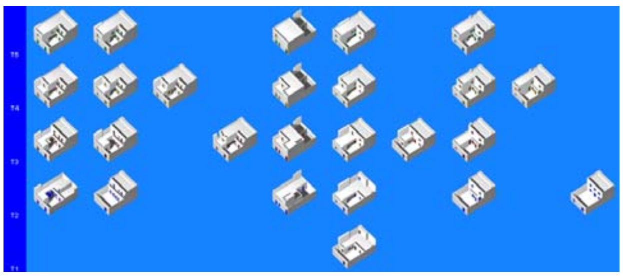


Figure II-2: Malagueira initial studies

The resulting grammar yields dozens of designs (see Figure II-3, 4). To evaluate the designs, Duarte consulted with Siza and showed him a matrix of housing designs that randomly included both the original and grammar-generated designs. Siza could only identify some of the designs and could not distinguish many of his designs from Duarte's, thus successfully proving the usefulness of shape grammars given the proper creation of rules.

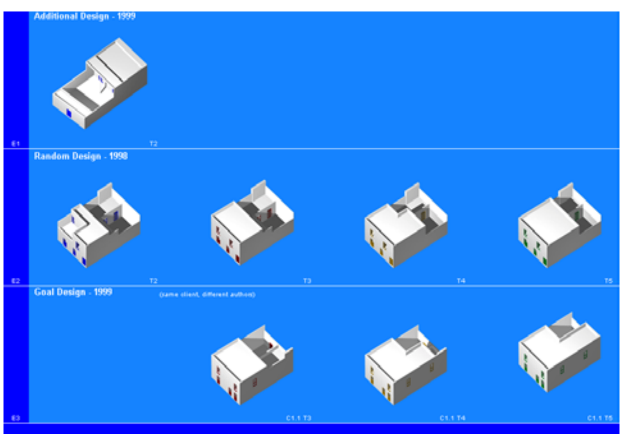


Figure II-3: Malagueira Housing grammar (a)

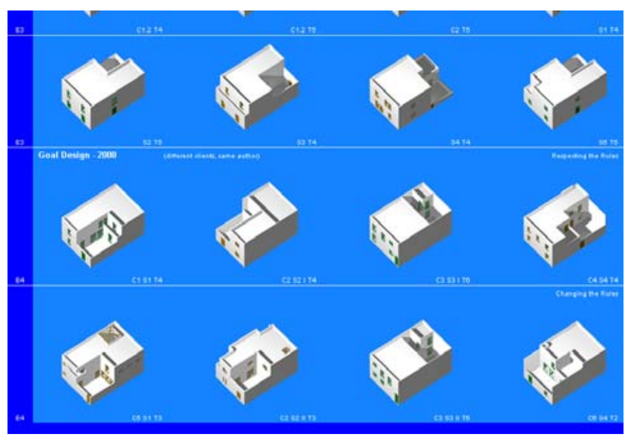


Figure II-4: Malagueira Housing grammar (b)

3. Harley Davidson Grammar

In 2002, Jonathan Cagan and Michael Pugliese published, "Capturing a Rebel: Modeling the Harley Davidson Brand through a Motorcycle Shape Grammar." This research investigated the use of shape grammars to identify key styling and engineering features vital to the Harvey Davidson Motorcycle brand. They began by examining existing designs (Figure II-5) and identified particular common features which provided the basis for writing the rules of design. Features like teardrop shaped fuel tank (Figure II-6), the wheel placement and connection points (Figure II-7), and the V-type engine configuration (Figure II-8) were among the many elements they abstracted to formulate their grammar.

Figure II-5: Harley Davidson Grammar

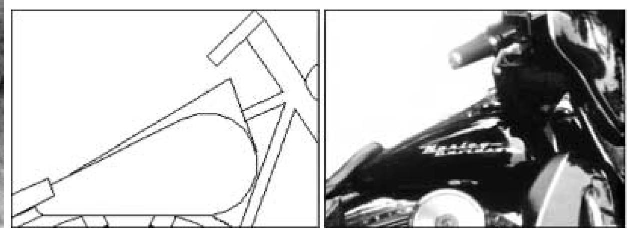


Figure II-6: Harley Davidson grammar – fuel tank

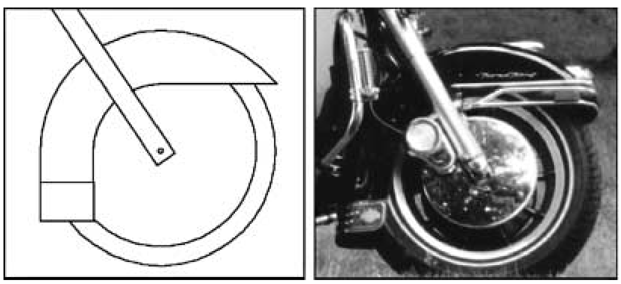


Figure II-7: Harley Davidson Grammar – wheel

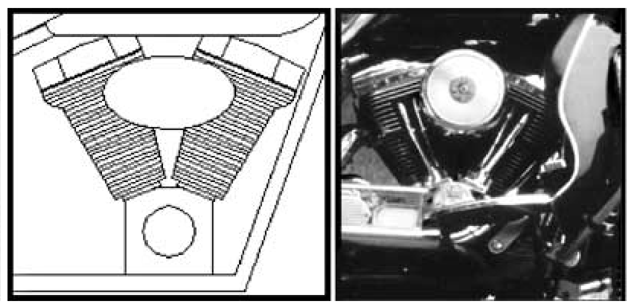


Figure II-8: Harley Davidson grammar - engine

Cagan and Pugliese generated numerous designs using 45 design rules in the motorcycle grammar. To evaluate their designs they conducted a comparative study (Figure II-9) in which they surveyed Harley Davidson owners by asking them to identify the closeness of these designs to what they perceived to be existing designs. 3 of the 10 designs presented had approval ratings of over 74%. One design had a 94% approval rating.

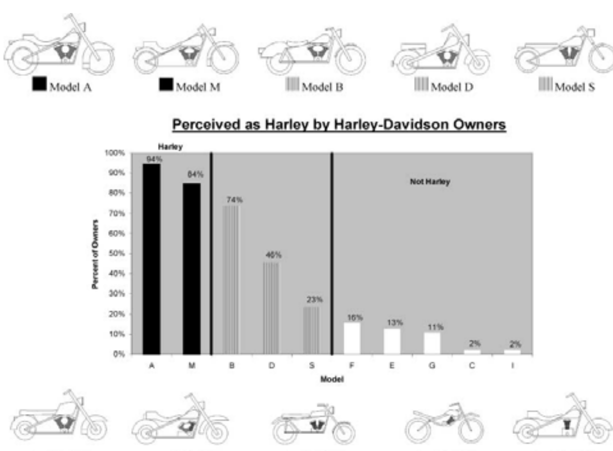


Figure II-9: Perceived as Harley by Harley Davidson Owners comparison chart

4. Buick Grammar

Soon after the motorcycle studies, Cagan, along with Jay McCormack and Craig Vogel, published, "Speaking the Buick Language: Capturing, Understanding, and Exploring Brand Identity with Shape Grammars." Like the motorcycle research, the Buick grammar was applied to the automobile, and these researchers studied the historical evolution of Buicks (Figure II-10, 11) to better understand the styling trends and their morphology.

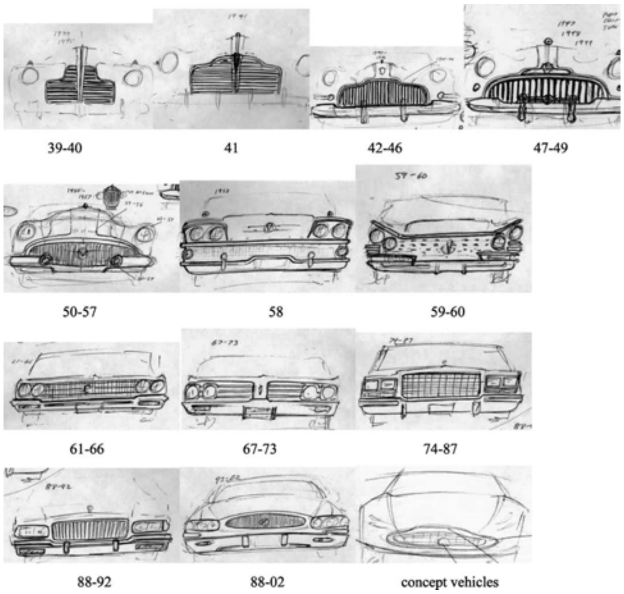


Figure II-10: Buick grammar – historic evolution

Figure II-11: Comparative study of the Buick Regal

> The Buick shape grammar has been used effectively to model shapes inherent to the Buick brand. The grammar provides the means for the studio, engineering, and marketing to communicate about the brand by supporting styles of communication appealing to each discipline...Discovering the limits of a feature by stretching its parameters must be done within the context of a Buick vehicle, as the brand is a gestalt of features, together defining the brand. [2]

Figure II-12: Buick La Cross concept vehicle

Figure II-13: Buick Cielo concept vehicle

[2] Cagan J., McCormack J.P., Vogel C.M., 2004, Speaking the Buick Language: Capturing, Understanding, and Exploring Brand Identity with Shape Grammars. *Design Studies,* vol. 25, no.1, pp. 1-29.

5. The BMW Grammar

The next two grammars are the result of student work from Professor Terry Knight's MIT course 4.201: Computational Design. Goncalo Ducla Soares studied BMW designs as part of his coursework. Like the Harley and Buick grammars, the BMW grammar attempts to capture key styling elements essential to the brand and to create rules for generating alternative designs. Soares began by studying the fascias of the 3, 5, 7, X5 and Z8 series brands (Figure II-14). After identifying the basic elements (Figure II-15), rules are generated for the derivation of the series in question (Figure II-16).

Figure II-14: Comparative study of BMW fascias

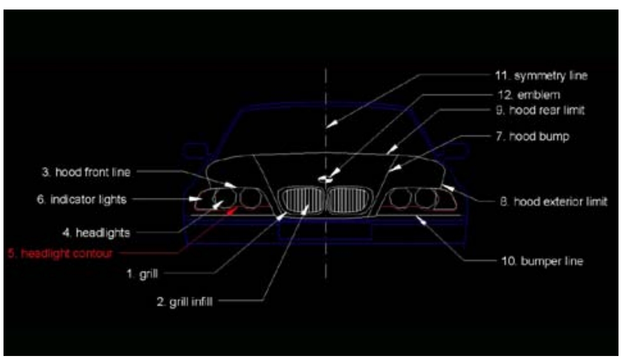


Figure II-15: BMW grammar – key elements

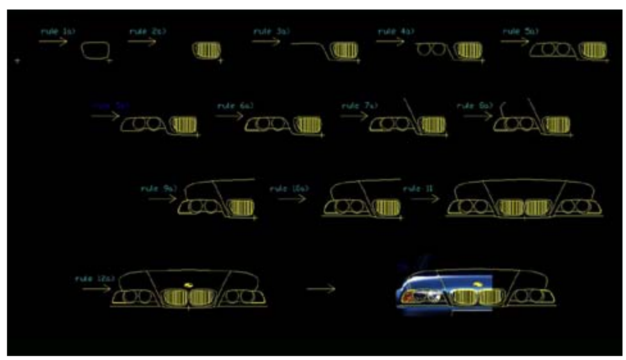


Figure II-16: BMW grammar derivation for 3 Series

Figure II-17 shows several BMW designs generated by the grammar. The challenge for shape grammars in the realm of mature industry products like cars, trucks, and motorcycles is in breaking preconceived notions of design form. Designed artifacts like BMWs and Buicks are evolutionary products that change quite slowly over time and are influenced by the design trends in the few years before the date of production. The evaluation of grammar-generated designs suffers because the evaluation reverts only to basic themes like proportion or form. The value in grammatical research is the ability to extend the design process by constructing new parameters for evaluation and synthesis.

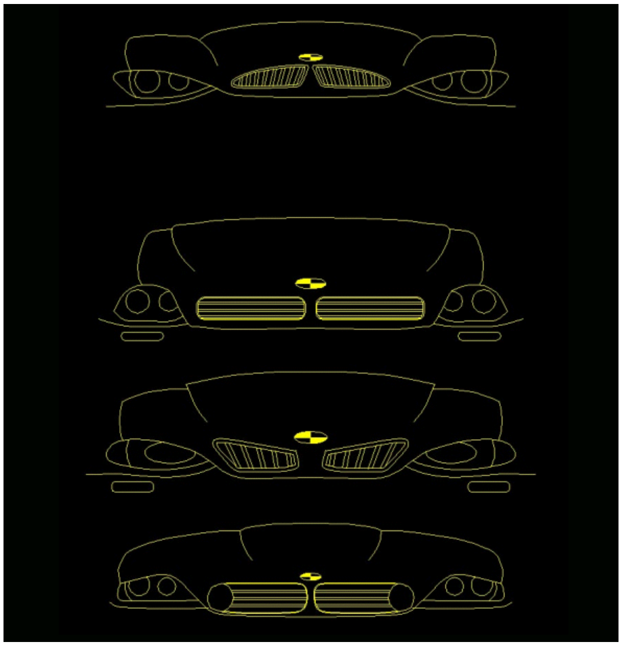


Figure II-17: BMW generated designs from the grammar

6: The Beetle Grammar

Saeed Arida also participated in Terry Knight's design course in 2002. He investigated the Beetle and created parametric additive and subtractive rules for his grammar (Figure I-18, 19). J Mays's design calling for the use of pure geometric forms heavily influenced the new Beetle. The design is readily conducive to shape grammar analysis. Figure II-20 shows the derivation of the Beetle through Arida's rules. This study differs from the Buick and BMW studies, as the side view is the key elevation in question.

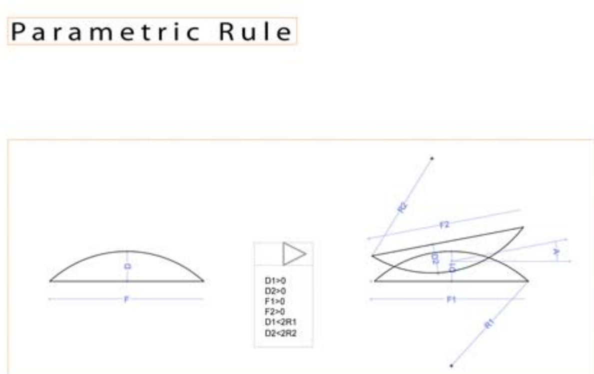


Figure II-18: Beetle Parametric rule

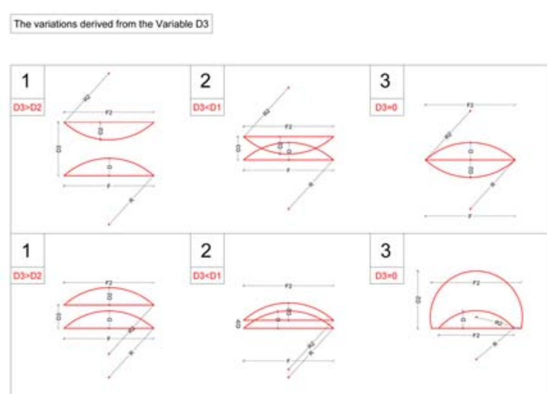


Figure II-19: Additive rules for the grammar

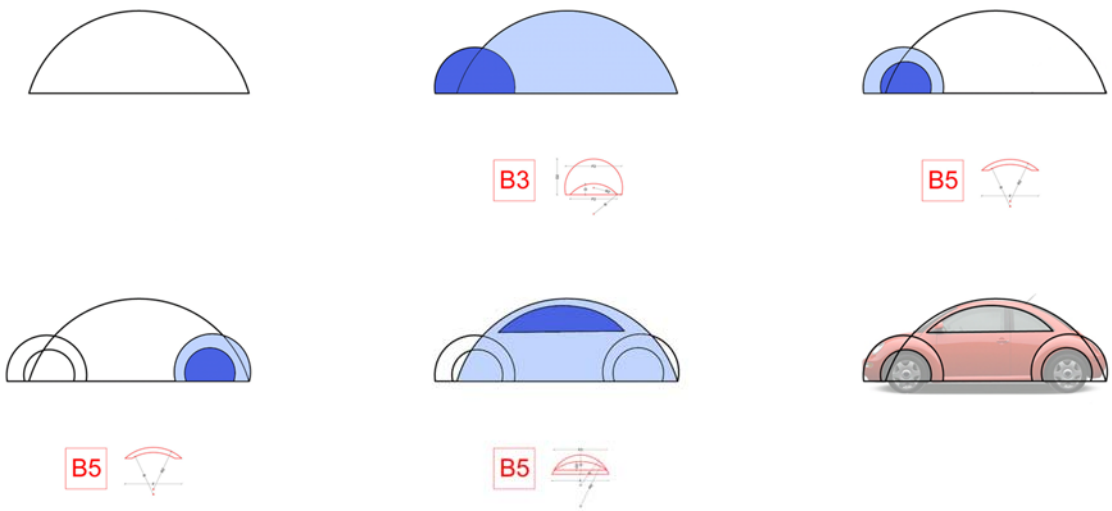


Figure II-20: Beetle grammar derivation

Figures II-21, 22, 23, and 24 are a sampling of the generated Beetle designs. Varying the rule application sequence produces the car design. Some designs are very subtle, such as Figure II-21, where the slight change is in the window line. Other designs start to suggest a deviation from envelope outline. The benefit of shape grammars is that they can improve by changes in the rules. In the case of Figure II-24, the cabin begins to break from the overall form of the Beetle. If this is a not a desired effect, then it is simple to add another rule that does prevent all geometric manipulation from breaking the overall envelope outline.

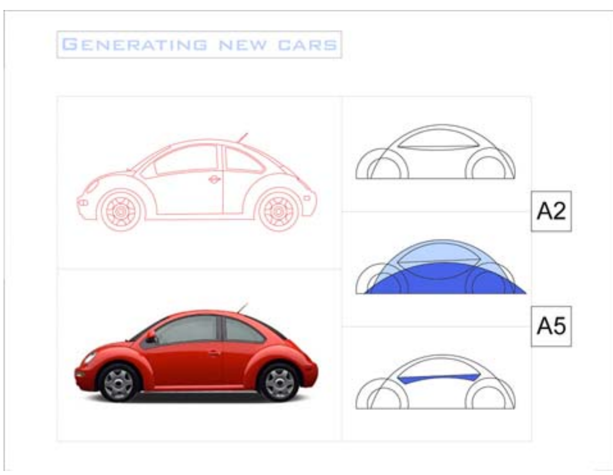


Figure II-21: Beetle grammar design (A)

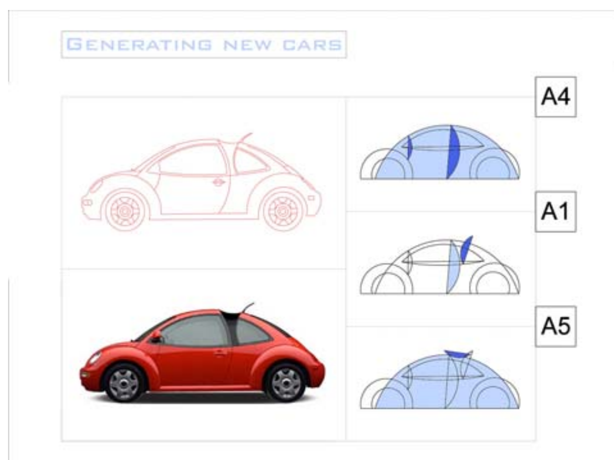


Figure II-22: Beetle grammar design (B)

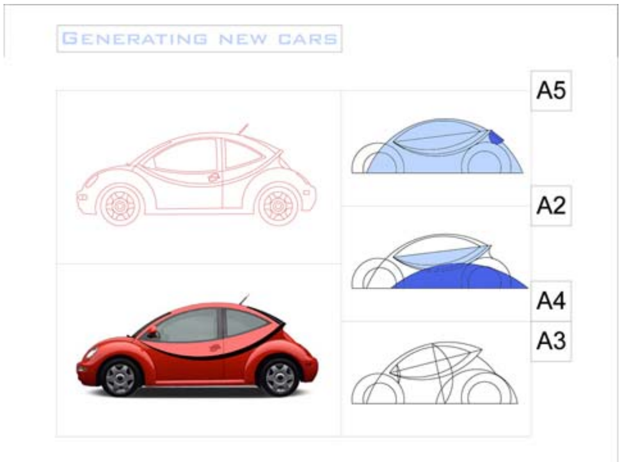


Figure II-23: Beetle grammar design (C)

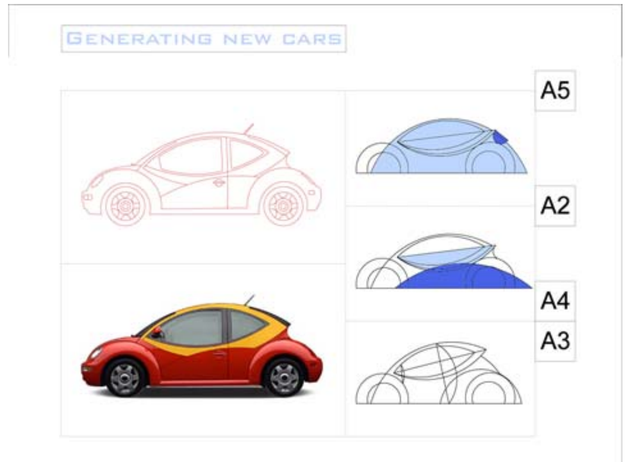


Figure II-24: Beetle grammar design (D)

PART III. THE PRODUCT GRAMMAR

The shape grammar formalism provides a method for which designers can generate many designs that can be evaluated through the setting of design and engineering rules. Parametric design methods allow for variation and flexiblity within generative design practices in order to accommodate applied manufacturing and fabrication constraints. The mapping of solution spaces allows the designer to see all possible configurations among components and assemblies at different architectural levels. The product grammar is the synthesis of these research themes. To illustrate this, Part III is divided into 4 distinct sections: (1) In **How to define a product grammar**, William J. Mitchell describes how a product grammar should be constructed for any given product. (2) **Case Study: the Pencil Grammar** references the pencil example developed in MAS968 by William J. Mitchell, James Gips, Will Lark, Franco Vairani, and Axel Kilian. This example describes how a product grammar is developed for a writing implement. (3) **Example 1: Innovations in Seating**, references the egress/ingress studies conducted by Axel Kilian. This example describes how the product grammar allows for the synthesis of the different nodes and branches of the tree structure at the subsystem level to allow for innovation. (4) **Example 2: the Motor Wheel** references the hubless-wheel with embedded suspension and electric motors developed by Patrik Künzler in MAS 966 and MAS 968. This example describes an alternative method to the product grammar's synthesis of the different branches of the tree structure at the subsystem level. (5) **Example 3: New Architecture for the Car**, describes how to use the product grammar to create a new high level structuring of a product that allows for flexibility and emergent innovation to inform the design decisions.

1. HOW TO WRITE A PRODUCT GRAMMAR[3] (William J. Mitchell)

1. Consider a complete 3D CAD model of an existing or conjectural product design that interests you. Look at the way elements and sub-assemblies are spatially nested one within the other. Construct a tree diagram showing this nesting, with the complete product at the top of the tree and the smallest elements you wish to consider, such as nuts and bolts, at the bottom.

2. From a materials, fabrication, and supply-chain perspective, this subdivision into sub-assemblies represented by each node in the tree is an opportunity to change materials, manufacturing processes, and suppliers. Think critically about whether the subdivision you have made is a practical and useful one from this perspective. If not, consider changing it.

3. From an assembly perspective, the sub-division at a node represents one or more joints, with certain tolerances, that must be formed at some stage during the assembly process. Think about the nature of these joints, and the process of forming them. Will they be easy or difficult to form, cheap or expensive? Who will form them, and what sorts of skills, tools, and machinery might be required? Will the result of forming the joints by a physically stable and robust sub-assembly that can conveniently be picked up and moved around during the assembly process? Will it require special jigs, clamps, formwork etc? If the subdivision you have made does not make practical sense from this perspective, consider changing it.

4. From a functional perspective, the sub-division represents an assignment of functions to sub-assemblies. At each node, write down a list of the functions provided (output) and required (input) by the sub-assembly considered as a functioning subsystem in use. (Think of this as the perspective of functional anatomy.) Does the complete system provide the functions you want? From an engineering viewpoint, does each element and subsystem in the tree seem feasible? If your subdivision does not have a suitable functional interpretation, consider changing it.

5. From a finer-grained functional perspective, each joint that you form is a functional interface between subsystems, and it must achieve certain physical properties – such as transmission of a force or an

[3] Mitchell, William J., "How to Write a Product Grammar," February 20, 2004.

electric current, thermal or electrical insulation, rigidity or freedom of movement, or seal against leakage of fluids – if the functional interface it to work. Are the functional interfaces that you need to achieve feasible? Will they produce reliability or maintenance problems?

6. From a parametric design perspective, each joint is an interface at which lower-level sub-assemblies must both spatially fit together and achieve the necessary functionality. The first step in creating a parametric model is to write down the constants, variables, and expressions that define these requirements. In effect, you define a set of sub-assembly interface standards, which must be maintained, at each node in the tree.

7. From a parametric variation perspective, consider the variables associated with each element and subsystem, and how these might be manipulated subject to maintaining the interface standards that you have defined? Which of these variables do you want to take as your independent design variables, and how do you want to propagate dependencies up or down through the tree? What does a particular choice of independent variables and propagation scheme imply for design control and expressiveness? How can you set up the model so that it effectively supports design exploration?

8. From a combinatorial perspective, consider ways to switch out entire branches of the tree, at any level (subject to maintaining interface requirements) and replace them with others that have different formal, functional, and manufacturing implications. (These switches correspond to alternative shape-substitution rules in a shape grammar.) Consider the advantages and disadvantages of the various options, and how these might change as the context of the surrounding complete system changes. Consider whether such switches represent design options for a supplier, or whether they might be customer choices within the framework of some customization strategy. Consider the implications of options for brand identity, part lifecycle and repair and replacement strategy, and recycling.

9. Look for ways to expand the solution space by taking grammars produced by your friends and colleagues, and integrating elements and sub-assemblies from these grammars as options into your grammar. Think of this as the recombinant stage – a new form of creative collaboration that has the potential to open up new and unexpected design possibilities. Ultimately, you might think of organizing an open-source, peer-to-peer network to support exchange and recombination of element and sub-assembly models.

10. When the combinatorial and parametric solution spaces defined by your grammar become large, consider implementing search algorithms that can traverse the spaces to find particular designs that match specified criteria.

2. CASE STUDY: THE PENCIL GRAMMAR[4] (William J. Mitchell)

Product grammars are related to phrase-structure grammars as employed in linguistics and computer science and shape grammars as employed in two-dimensional and three-dimensional design. They provide a consistent, logical framework for:

1. Capturing practical knowledge about product design in CAD-friendly format.

2. Integrating new inventions and design ideas.

3. Partitioning design tasks and supply chains, and organizing collaborative work.

4. Critically rethinking the functions, forms, and fabrication of products.

[4] Mitchell, William J., “The Pencil Grammar,” April 2004.

This working paper introduces product grammars and illustrates their application through some simple examples.

A. Parsing products

Just as a sentence can be parsed into parts of speech – that is, words and phrases combined in a particular way to produce that sentence's meaning – so a manufactured product may be parsed into a hierarchy of components and subassemblies combined in a particular way to produce that product's function. In other words, the strategy of parsing a complex object into simpler parts can usefully be generalized from one-dimensional strings of meaningful symbols to three-dimensional assemblies of functional components. Parsing, in this fashion, shows how a product is put together and explains how it works. Where the syntax tree of a sentence is defined by ordering under *substring* relationships, however, the syntax tree of a product is established by ordering under *subassembly* relationships. This idea is best developed informally, by means of a simple example.

Consider a stick of chalk – one of the simplest imaginable writing instruments. A single cylinder of uniform material elegantly provides a writing tip, a continuous supply of material to that tip, a shape that can comfortably be grasped, and overall structural integrity. These are the sub-functions that combine to provide the high-level function of enabling writing. But there is no differentiation of the chalk into discrete components, so the syntax tree reduces to a single node. There is just a single, multifunctional component that might be produced by a suitable machine in one fabrication step, and no assembly is required.

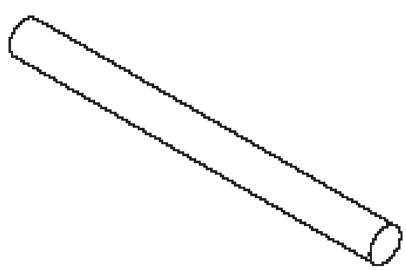


Figure III-1: A stick of chalk

Figure III-2: Chalk syntax tree, single node

A crayon is slightly more complex. It is also a single shape of uniform material, but the properties of the material and the fabrication process allow it to have a tip that is more effectively optimized for writing. If we consider it as a parametric object, the crayon has more parameters than a stick of chalk, and these parameters have wider ranges of realistic variation, so in practice, crayons come in a huge variety of sizes and shapes.

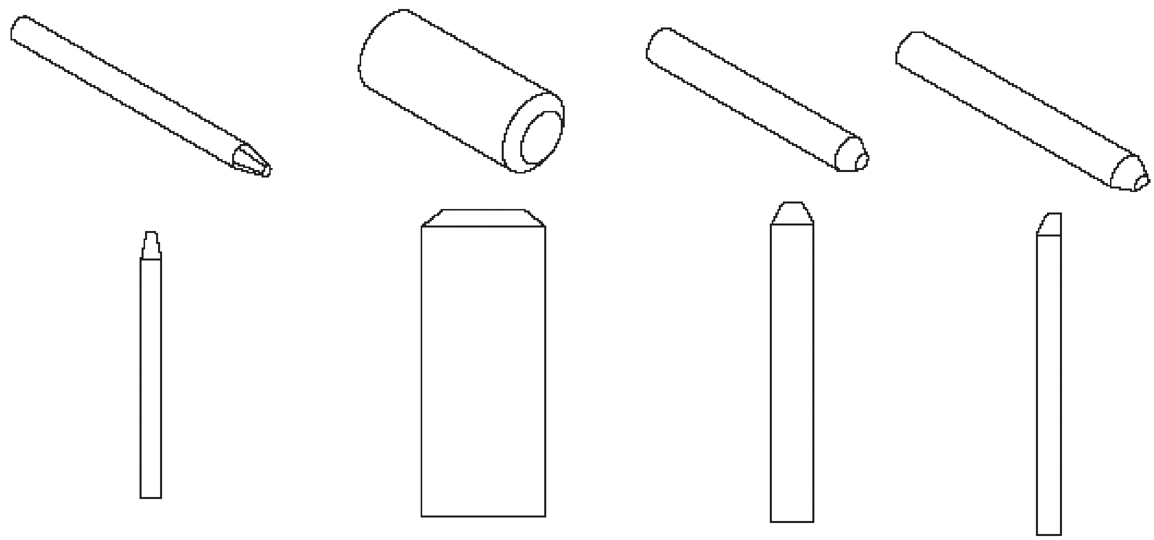


Figure III-3: Parametric model of a crayon and some of the possible instances

A second way to refine the functionality of a crayon is to provide a more comfortable grip by adding a paper sleeve. This divides the syntax tree into two branches, corresponding to the writing element and the sleeve. The sleeve optimizes its function by making the writing instrument less slippery to grasp and keeping fingers from getting smeared by direct contact with the writing material. It also creates the possibility of ancillary functions, such as carrying decoration, labels, or advertising. The writing element continues to provide the tip, material supply, and structural integrity. The two components must be produced separately, and then assembled to create the complete product.

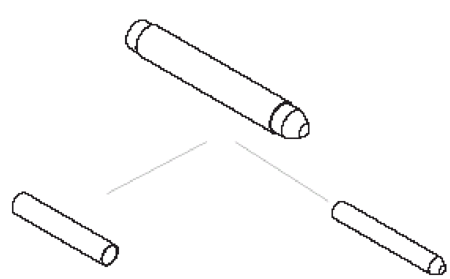


Figure III-4: Wax crayon with a paper sleeve

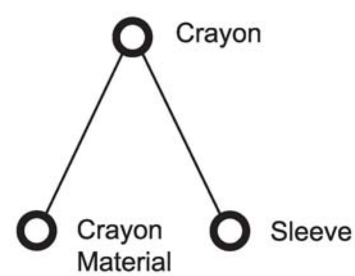
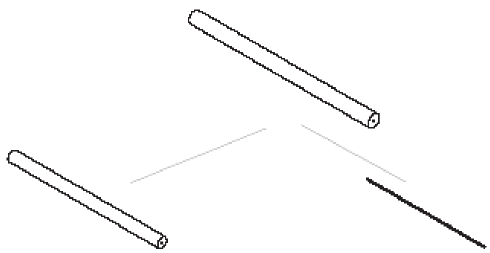


Figure III-5: Crayon syntax tree

A simple pencil, like a sleeved crayon, has a two-branch syntax tree, with a thin graphite rod providing the writing tip and material supply and the wooden sleeve providing the grip. From this perspective, it is a material and dimensional variant of the sleeved crayon. However, since the graphite rod is fragile, the function of structural integrity must be provided in another way. It therefore moves from the writing element to the sleeve. So the structure of the syntax tree remains the same, but a functional label is reassigned from one node to another.



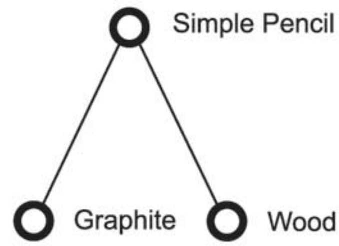
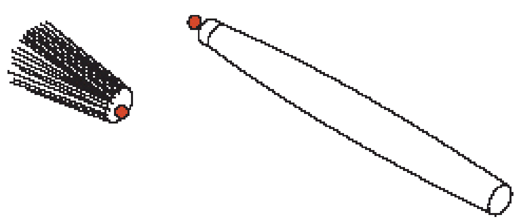


Figure III-6: A simple pencil

Figure III-7: Simple pencil tree

With the crayon and the pencil, a two-component assembly is realized through the spatial relationship of nesting – that is, by fitting the writing element within the sleeve. But a two-component assembly may also be realized through end-to-end connection of components. This alternative spatial interpretation of the two-branch tree yields a different architecture for writing instruments, that of the brush or steel-nibbed pen consisting of a handle connected to a combined writing tip and writing fluid reservoir.



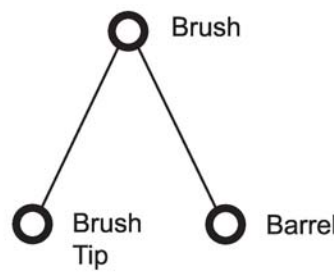


Figure III-8: The paintbrush and the pen, spatial realizations by means of end-to-end connections

Figure III-9: Brush syntax tree

Chalks, crayons, and pencils all suffer from the disadvantage that their method of providing material supply has the undesirable side-effect of eroding away the grip until the instrument eventually becomes too small to grasp comfortably, and has to be discarded. To overcome this, a designer might replace the simple, monolithic system for supplying material with a more complex sub-assembly with an internal reservoir, as with a felt-tip marker or ballpoint pen. Thus there is a split at the node representing the writing element.

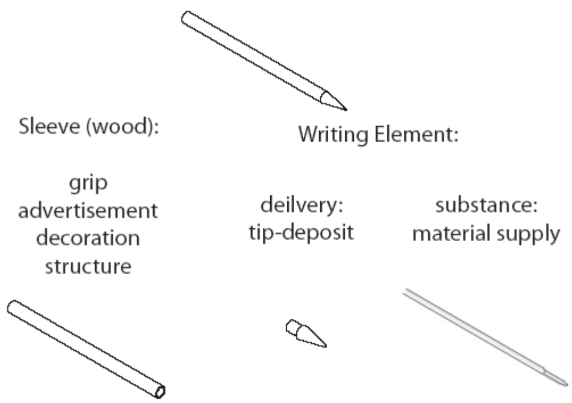


Figure III-10: Simple ballpoint pen

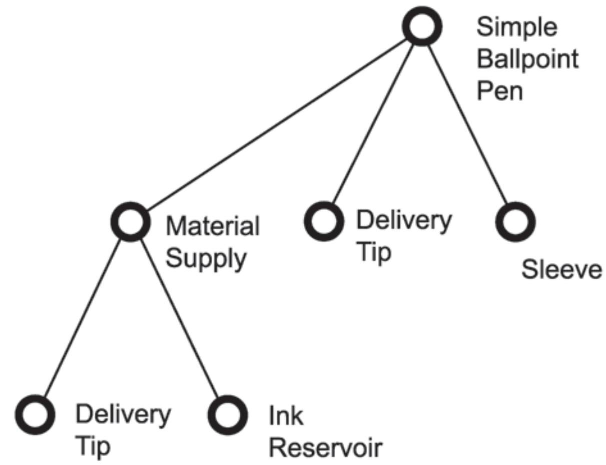


Figure III-11: Simple ballpoint pen syntax tree

Similarly, paintbrushes and simple pens have the disadvantage that their reservoirs are of limited capacity and soon run out, requiring frequent dipping in a paint pot or inkwell. This limitation can be transcended by nesting a larger reservoir within the handle to produce a cartridge fountain pen, felt-tip marker, or – once again – ballpoint pen. The line of reasoning is different from that which begins with a pencil, but the resulting architecture is much the same.

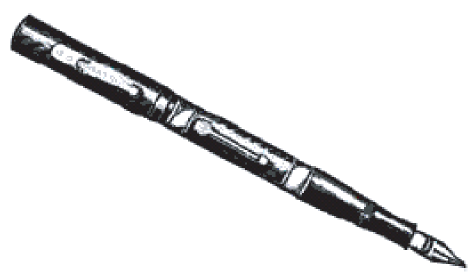


Figure III-12: Cartridge fountain pen

The trouble with felt-tip markers and cheap ballpoint pens is that their internal material reservoirs have finite capacity, and they have to be thrown away when the supply of material runs out. To overcome this, a designer might introduce the idea of a replenishable or replaceable reservoir, as with fountain pens, more expensive ballpoint pens, and mechanical pencils. The possibilities include replaceable cartridges of various kinds, pump-action fountain pens, and propelling pencils. Development of these possibilities introduces more elements and sub-assemblies, with their own specialized sub-functions, and makes the syntax tree deeper and more complex. They also open up the possibility that the sleeve can become an object of ostentatious display – as with gold-plated, diamond-encrusted fountain pens. Assembly of the complete product is now a complex process.

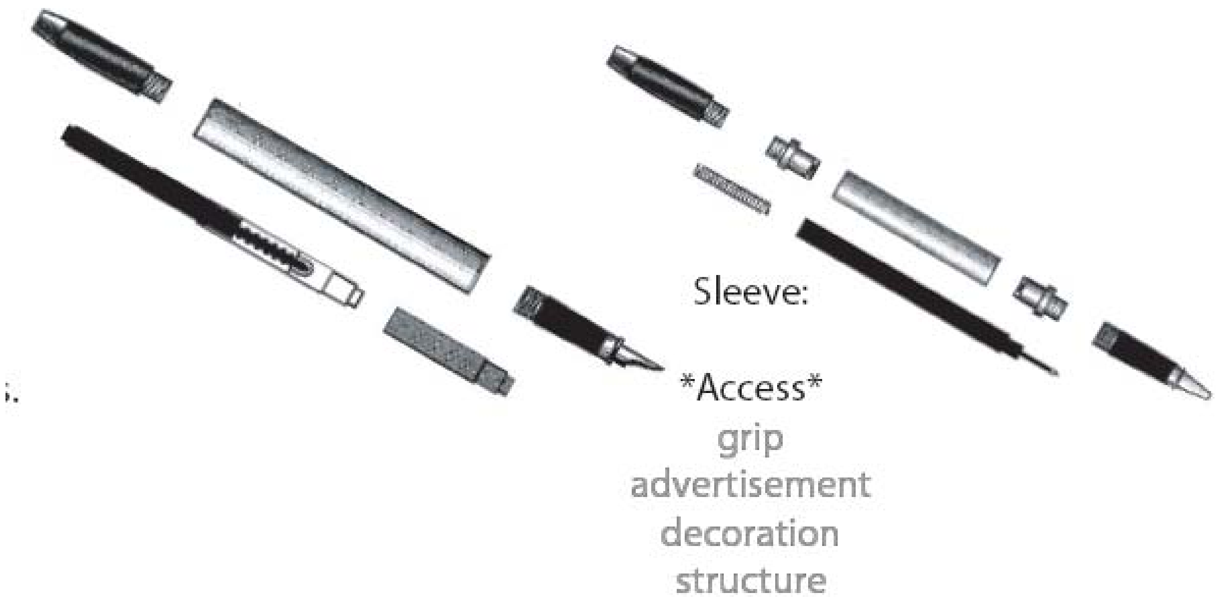


Figure III-13: Architectures for more durable and expensive writing instruments

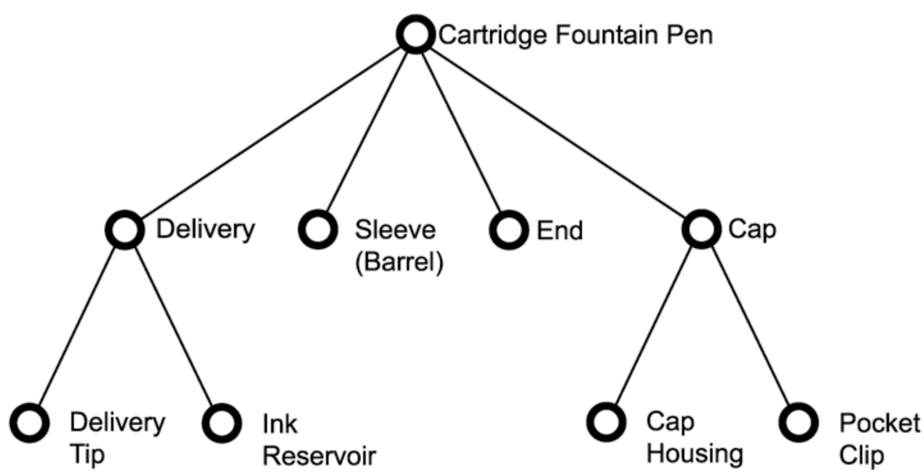


Figure III-14: Cartridge syntax tree

The non-writing end of a writing instrument provides both the opportunity and sometimes the need to introduce additional components that extend functionality. It might, for example, be embellished with an eraser, a metal cap to prevent chewing, a clip for attachment to a pocket, or a decorative motif. If the instrument incorporates a screw or pump mechanism, then this may be attached conveniently at the same location. In some clever designs, a single sub-assembly provides several of these functions.

Figure III-15: Introducing additional functions

Sometimes, as with markers that dry out, the writing tip requires protection, and this can straightforwardly be provided by a friction-fit or screw cap. Alternatively, a retraction mechanism for the tip provides another form of protection.

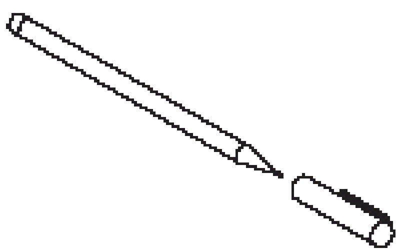


Figure III-16: Protecting the tip

This sort of analysis can be extended more-or-less indefinitely, but the essential idea should now be clear. The overall function of a product can recursively be broken down into sub-functions that combine to produce it. A tree diagram showing how these sub-functions map onto components and sub-assemblies – that is, the grouping and hierarchy of the sub-functions – depicts the *functional schema* of the product. A functional schema can be provided with a particular *spatial interpretation* by defining the shapes of components and the spatial relationships among components and among sub-assemblies. In general, there will be many ways to organize a set of sub-functions into a functional schema, then many ways to provide a given functional schema with spatial interpretations.

Figure III-17: From a list of sub-functions to a functional schema and a particular spatial interpretation

B. Abstraction and interfaces

For many design purposes, the internal details of components and sub-assemblies are unimportant, and can be abstracted away from by modeling only the outer spatial envelope. The tree diagram for a product, drawn in this way, thus illustrates a hierarchy of abstraction layers – much like computer code that is organized into a hierarchy of subroutines, procedures, or objects.

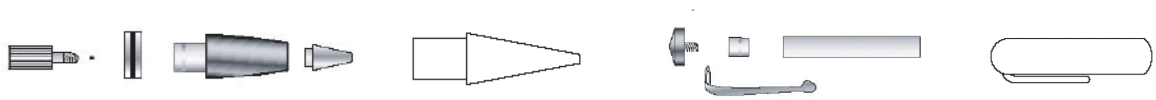


Figure III-18: Spatial envelopes define an abstraction hierarchy

Assembly of two components to create a sub-assembly requires attachment of some part of one to some part of the other. The attached part of a component – that is, its interface to the other component – may be a point, a line, a surface shape, a volumetric shape, or some combination of these. For successful assembly, the interface of each component must match that of the other – as for example, when the diameter of a pencil's graphite rod matches the diameter of the wooden sleeve's cylindrical hole. When the interfaces that must match up among components and subsystems are graphically identified, the tree diagram for a product makes the logic of assembly explicit.

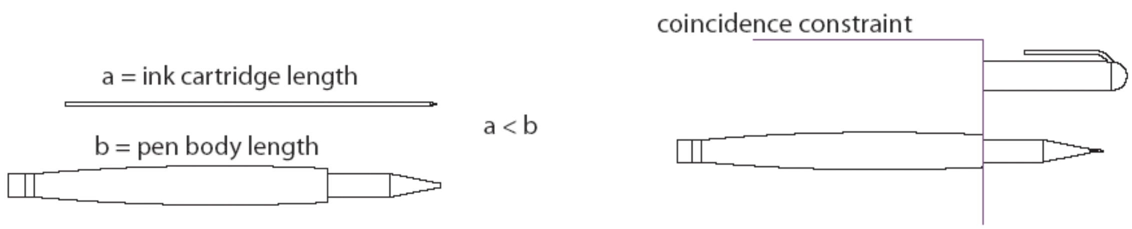


Figure III-19: Graphically identifying the interfaces makes the logic of assembly explicit

For the assembled product to function as intended, the interfaces among components and sub-assemblies must not only match, they must transfer something. For example, the interface between a pair of structural components might transfer axial forces, shear forces, or bending moments. Fluids cross interfaces in fluid-flow systems, current crosses interfaces in electrical systems, and bits cross interfaces in computation and communication systems – of both the hardware and software kinds. With a sleeved crayon or a simple pencil, the interfaces are structural, playing the simple role of holding the components securely together. In fountain pens, however, there are fluid-transfer interfaces – which, unfortunately, do not always perform as they should. And, in propelling pencils and the like, there are mechanical linkages.

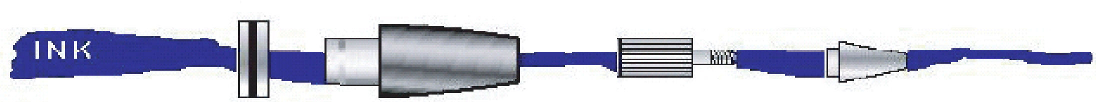


Figure III-20: Different types of interfaces within an assembly

In general, a component or sub-assembly's interfaces severely restrict the spatial relationships it can form with other components and sub-assemblies. A replaceable nib can fit into a pen handle in just one way. Perhaps the cap can attach to the handle in two ways – to the writing end when the pen is not in use, and to the non-writing end when it is. Two Lego blocks can snap together in a larger number of ways, but the possibilities are still discrete and finite. Two wooden Froebel blocks might be glued together in a face-to-face relationship that admits of continuous variation in relative position and orientation.

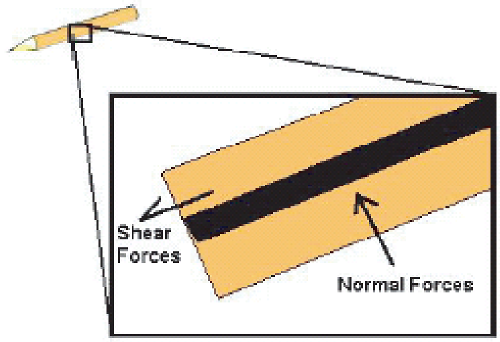


Figure III-21: The physical properties of interfaces restrict spatial relationships

C. Standardized interfaces, substitution, and replacement rules

If the essentials of the relevant interfaces are preserved, it is possible to replace one component or sub-assembly for another within an assembly to produce a formal and functional variant of a product. In a box of colored pencils, for example, the interface between the lead and the sleeve takes a standard form in each instance, but the colors of the leads vary. And, in a pen designed to take interchangeable nibs that provide varying line thicknesses and qualities, one nib screws out or slips out to be replaced by another.

The substitutions that are possible with a given set of components and their interfaces can be described by means of replacement rules. Much as with phrase-structure grammars and shape grammars, each such rule has a left side and a right side. The left side shows a sub-assembly that is eligible for replacement, and the right side shows the outcome of the replacement operation.

Figure III-22: Replacement rules specify alternative configurations

A replacement rule may apply not only to fully specified parts, but also to parametric models of parts. In this case, the rule specifies the relationship of the parameters of one component or sub-assembly to those of the other. Instead of specifying a constant for the diameter of a pencil lead, for example, a rule for combining the lead with its holder might specify that the outer diameter of the lead is equal to the inner diameter of the holder.

Figure III-23: A replacement rule specifies a relationship of parameters

D. Fabrication, assembly, and supply chains

From a fabrication perspective, any branch in the syntax tree for a product provides an opportunity to change materials or fabrication processes. At the same time, it introduces a joint that must be formed with appropriate tolerances, and an assembly step. Thus the syntax tree provides a clear framework for considering manufacturability and supply chain organization.

The syntax tree also provides a structure for deciding which parts of a product are to be taken as “given,” and executed using existing components and assemblies, and which are to be custom designed to meet particular needs of the current context. This distinction might, for example, separate mass-produced, standardized infrastructure from plug-in options.

In practice, development of a practical product grammar must take account simultaneously of functional, fabrication and material, assembly, and supply chain issues. The structure of the syntax tree should respond to these considerations.

E. Product grammars specify languages of designs

Product grammars may be developed and employed informally, much as speakers typically employ the vocabulary and syntax of a language without precisely defining all the rules. Where necessary, however, a product grammar can rigorously be formalized in the following way. A product grammar consists of:

1. A starting component. This may be a low-level part that provides a convenient starting point for building up an assembly, or it might be a high-level organizational diagram, consisting of construction lines, etc, that provides an abstract framework to guide the design.

2. A vocabulary of elementary components.

3. A set of sub-assembly replacement rules.
Designs in the language specified by the grammar are derived by recursive application of the replacement rules to the starting component.

3. EXAMPLE 1: INNOVATIONS IN SEATING

The fountain pen grammar yields a three-level syntax tree as discussed in the pencil case study. It is imaginable that the syntax tree could be expanded to many more levels if we were to dissect the ink delivery system even further. In the automotive space, like other products with thousands of components and subcomponent syntaxes, tree structures can be hundreds of levels in sophistication with many overlapping branch nodes. Interpretations of such structures also vary depending upon which perspective taken. For the purposes of this thesis, I will suggest a relatively simple interpretation of a traditional car syntax tree and then derive solution spaces by applying the abstraction, substitution, replacement, and standardization techniques.

Innovations in automotive seating have been incremental over the last 20 years, with the introduction of electrically powered memory seats, seat warmers, air-conditioned surfaces, and the embedding of sensing technologies. The innovations have been additive, but seats have not taken on radical new forms since the introduction of seatbelts and airbags. This study began not as an investigation into chairs in automobiles *per se,* but as an inquiry into the theme of egress/ingress initiated by Axel Kilian's design studies at the Gehry office. Spurred on by Frank Gehry's interest in exploring easier and more comfortable ways to get in and out of vehicles, he began producing numerous study models that mapped different solutions.

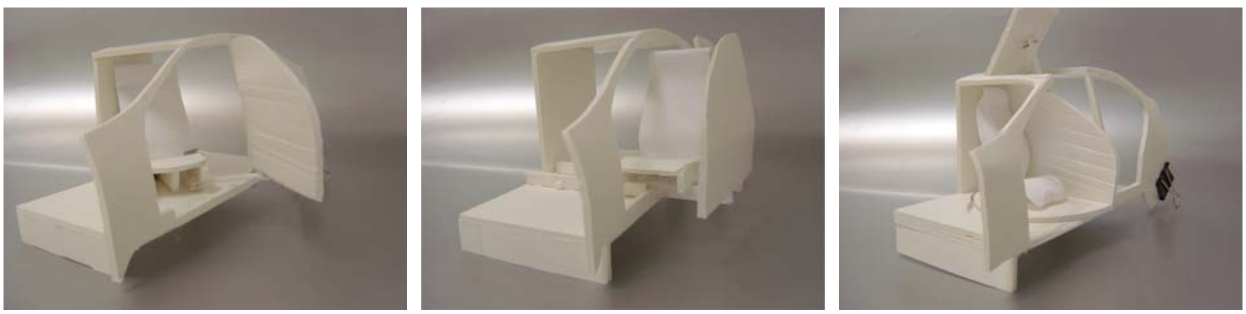


Figure III-24, 25, 26: Door studies by Axel Kilian at the Gehry offices

A. Parsing of Products

Beginning with a limited number of divisions at the highest level is often the best way to start the problem. Let us begin at the top of the architectural syntax tree by parsing the product similarly to what was done with pencil. The car grammar can be divided into a drive train and chassis at the highest level (see, fig. III-27). Other high-level systems like the interior, propulsion system, and body are subsets to these two major branches.

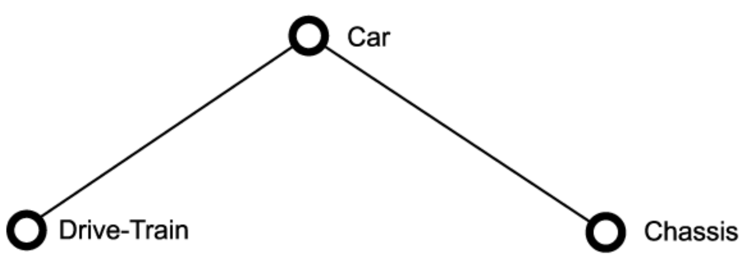


Figure III-27: Simple car syntax tree, 2 branches

An alternative parsing of the car product grammar can be seen in figure III-28, where the car's syntax tree immediately branches into 4 nodes. The major difference between a smaller versus larger number of branches is manufacturability and supply chain effects. Larger subdivisions in tree structures produces more flexibility in "subcontracting" each branch of the tree, thus greater standardization is key. Integration of components is the biggest challenge for abundant branch structures. For the sake of simplicity and continuity, the remainder of this thesis will divide the car grammar into the two major branches found in figure III-27.

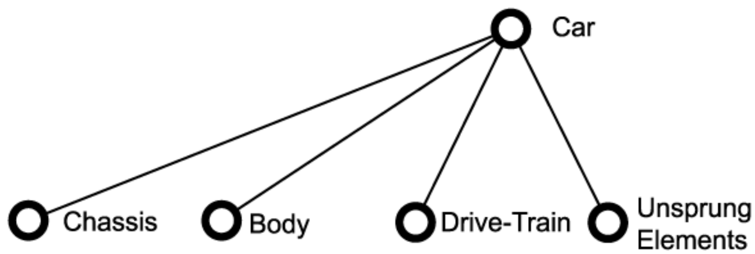


Figure III-28: Simple car syntax tree, 4 branches

Further mapping of the smaller syntax tree yields a two level structure shown in figure III-29. We are assuming a hybrid propulsion system, which requires an additional electric motor. The introduction of this alternative power source brings many benefits such as regenerative braking and better fuel economy. This will later play a significant role in defining a new high-level architecture. Suspension components like shocks, springs, and sway bars qualify as unsprung elements.

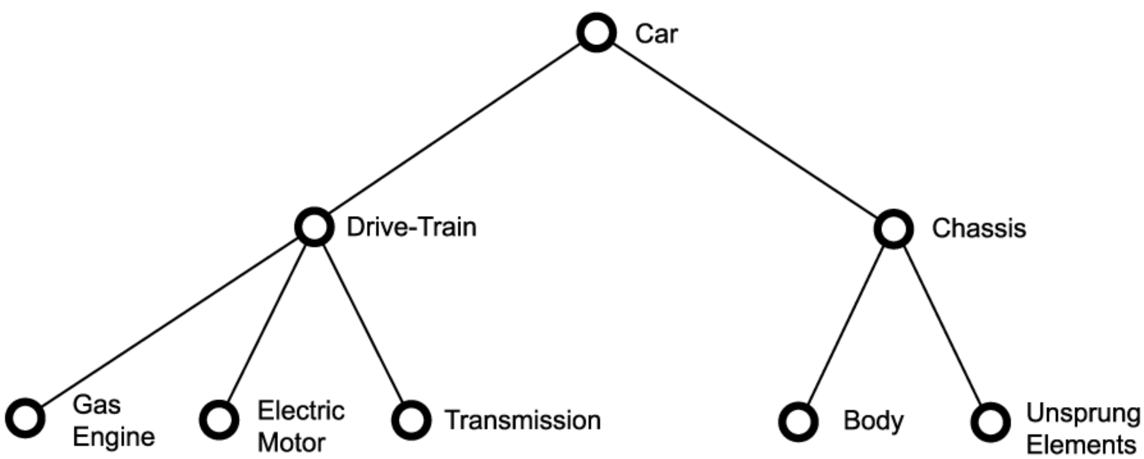


Figure III-29: Simple car syntax tree, 2 branches, 3 levels

Within this architecture, seating branches from the cabin node which stems from an earlier division of the body (see Figure III-30). The cabin also includes headliners, controls, interior safety (seat belts), etc. Also under the body includes the exterior body panels, lighting, and glazing systems. The seat itself can be further divided into horizontal and vertical supports, heating and cooling for the seat, and electro-mechanical ergonomic aides. Subdivisions at the component level allow the designer to abstract the function of the constituent parts in order to rationalize the integration of common functional elements.

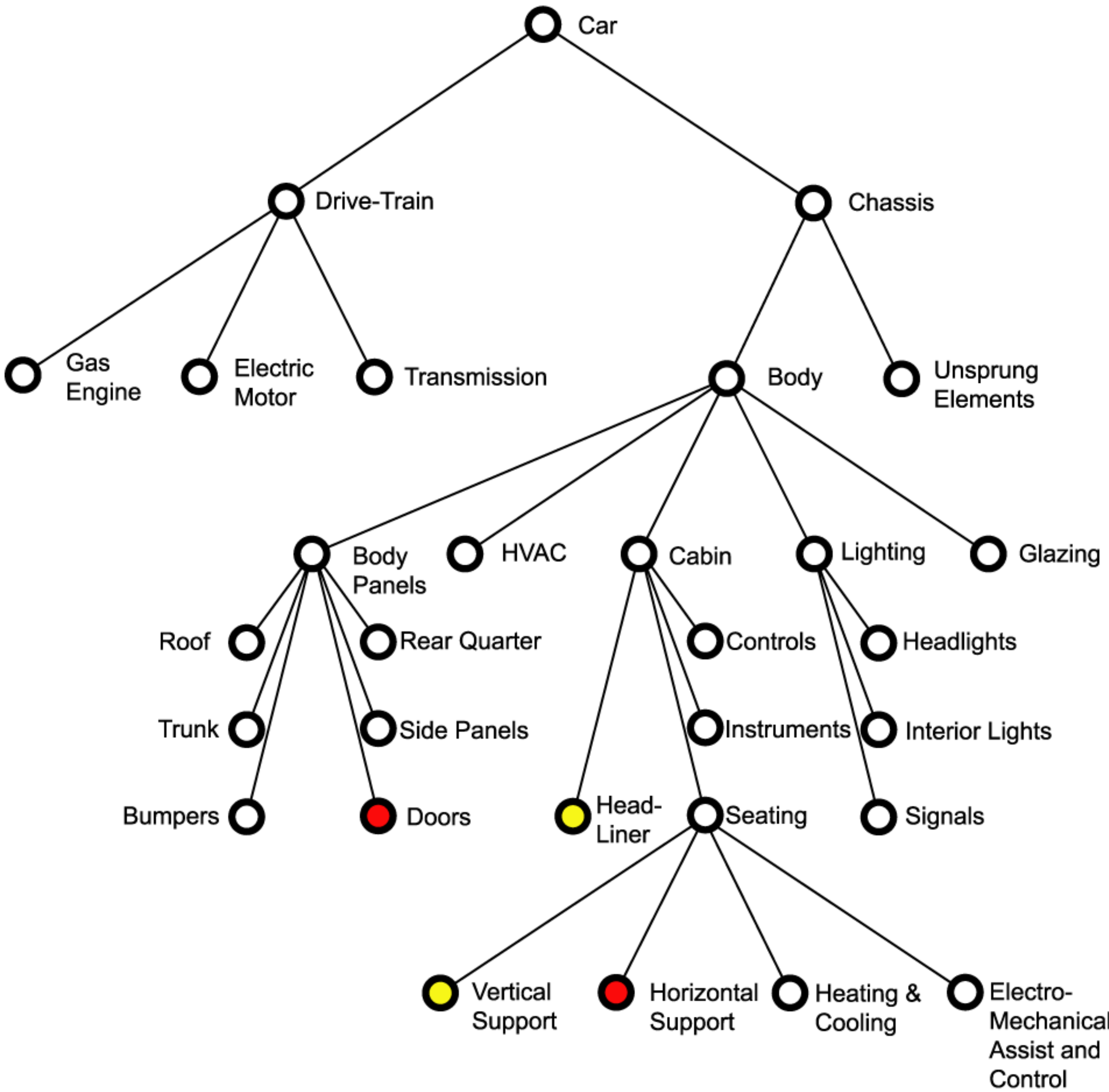


Figure III-30: Complete seat syntax tree

B. Abstraction and interfaces

Further investigation into the components that comprise seats allows the designer to separate the function from the form of assembly. A seat in a car can be viewed as furniture in a room, or as an appendage within the interior for sitting. The horizontal platform provides support from the forces of gravity and provides the necessary height from which the driver can view the road. The vertical support acts as a platform for safety devices like seat belts and provides a surface to rest your back. Both supports can be varied parametrically to fit within ergonomic constraints. Coincidently, doors are a critical part of the seating process because they are not only part of the experience, but also provide support. The doors provide protective enclosure and, in part, form the interior envelope for the cabin. By mapping functions (done in red and yellow in figure III-30), we can begin to abstract the necessary interface candidates.

C. Standardized interfaces, substitution, and replacement rules

Simple substitutions are an integral part of syntax tree organizational schemes. In the case of seats, we can substitute one seat for another given standard connection interfaces. Tires, rims, body panels can also work in a similar fashion. Figure III-32 illustrates how a simple replacement can lead to a radical reconfiguring of the syntax tree. By collapsing the colored nodes we have dramatically changed the problem of seats and the nature of egress and ingress in vehicles. Combining the red nodes (horizontal support + doors) and the yellow nodes (headliner + vertical support) the seat no longer is an entity, but is now an integral part of its context. Some benefits include easier access as the horizontal support and door swing out together creating a new rotational circulation pattern. The horizontal component provides an opportunity to structurally enhance the entire safety system. The value in using replacement and substitution rules is the ability to be flexible to offer other possible configurations. In the case of the headliner and vertical support, we can substitute the B-pillar as a connecting surface to the vertical support or maintain such a configuration and look for innovations within the subdivisions of the newly proposed design (Figure III-31).

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Figure III-31: Proposed seating configuration

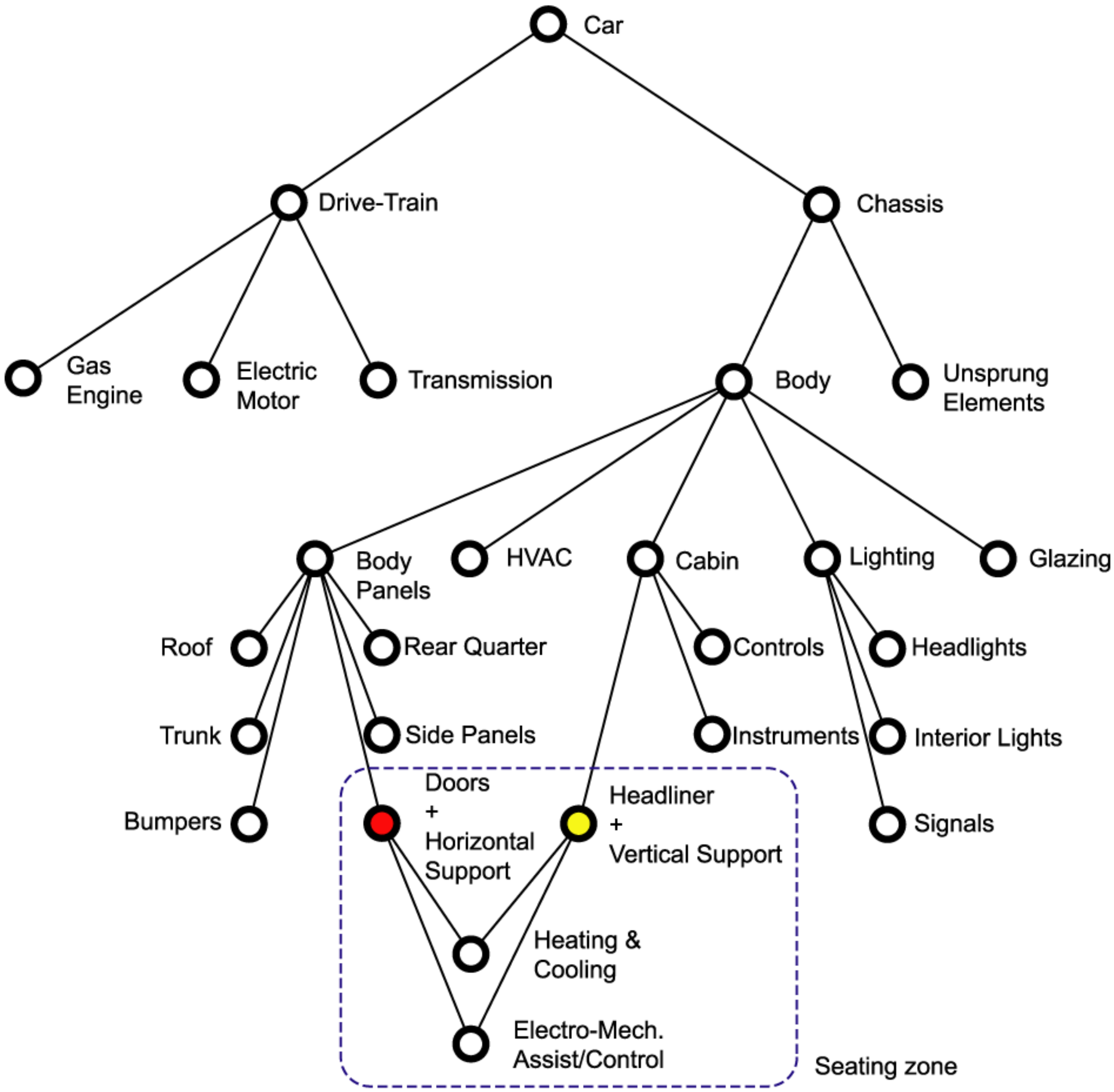

Figure III-32: The new seat design syntax tree

D. Fabrication, assembly, and supply chains

Radical rethinking of the seating has dramatic effects within fabrication cycles. A tier one supplier produces seats. That supplier will typically innovate only within a certain realm, such as the interior or the HVAC system. The user benefits must be balanced with marketing value and the added complexity with this new configuration. In this case, the door fabricator and the seat manufacturer have to work together in order to achieve this design. Assembly and fabrication will improve because two systems have been put together with those intents already in place. The CATIA models in figures III-33 and 34 illustrate the new configuration.

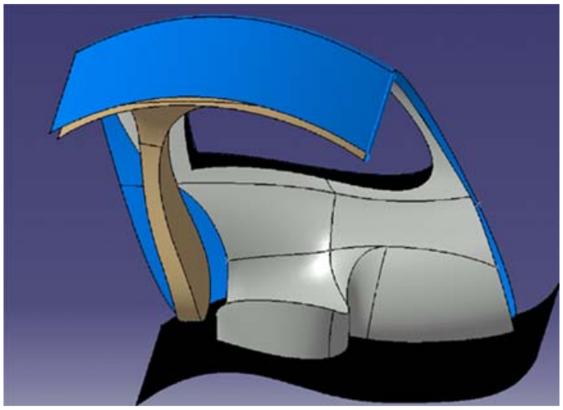

Figure III-33: 3D Catia Model of seat assembly

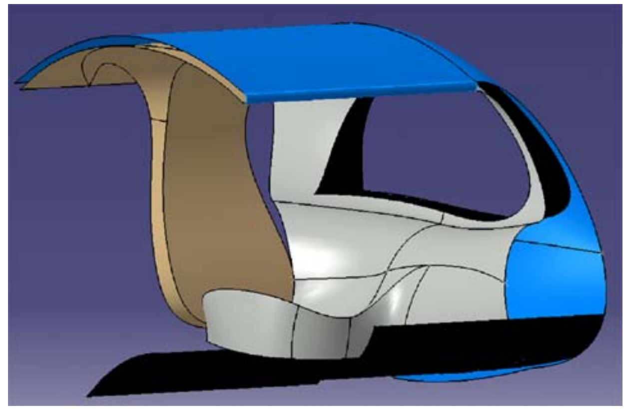

Figure III-34: 3D Model showing rotational access

E. Product grammars specify languages of designs (William J. Mitchell in italics)

Taking the pencil case study as a benchmark we can evaluate the seat grammar:

Product grammars may be developed and employed informally, much as speakers typically employ the vocabulary and syntax of a language without precisely defining all the rules. Where necessary, however, a product grammar can rigorously be formalized in the following way. A product grammar consists of:

1. A starting component. This may be a low-level part that provides a convenient starting point for building up an assembly, or it might be a high-level organizational diagram, consisting of construction lines, etc, that provides an abstract framework to guide the design.

The starting component consists of pieces such as horizontal and vertical supports, electro-mechanical aides, heating and cooling, etc. Place the seat within the cabin subsystem under the body system.

2. A vocabulary of elementary components.

The vocabulary includes elementary components like horizontal and vertical elements, enclosure envelopes, mechanical and electrical connections.

3. A set of sub-assembly replacement rules.

Replace elementary components and connections with components performing similar duties from other parts of the syntax tree.

Designs in the language specified by the grammar are derived by recursive application of the replacement rules to the starting component.

Recursive application yields new design solutions and new paths for exploration.

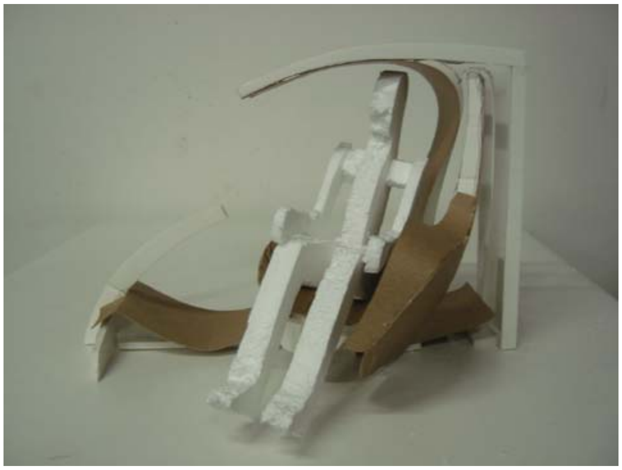

Figure III-35, 36: Physical model of new seat configuration

4. EXAMPLE 2: THE MOTOR WHEEL

The wheel has been a part of the car since the horse and carriage. It has been evolved from wooden wheels with wooden spokes to wheel assemblies with complex spoke rims made of titanium. The tremendous variety of sizes, patterns, textures, and materials in wheel designs lend themselves to generative design systems. Our task in MAS966 was to literally reinvent the wheel. As mentioned in the parametric design section, wheels can be defined by a number of constraints for aesthetics (proportions), functionalality (stability), and/or assembly (connections) reasons. The motor-wheel design moves beyond the traditional architecture suggested by the automotive industry in Figure III-37, of just a conventional substitution (i.e. changing your summer tires for winter tires), to a radical reconfiguration by absorbing other branches of the car syntax tree.

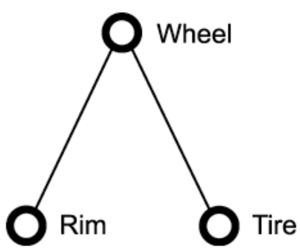

Figure III-37: Simple wheel syntax tree

CATIA training sessions were essential to dispensing shared knowledge and creating a common platform and vocabulary for innovation. Students learned basic 3D modeling, parametrics, and catia tree structures by building simple components like the tire. Similary, parametric design investigations started with simple components like wheels and axles. Example 2: the Motor Wheel, investigates the design of a hubless wheel with embedded suspension led by Patrik Künzler which orginiated from early modeling exercises in training. The following sections expound on the wheel grammar.

A. Parsing of Products

Assuming the standard car syntax tree, we can construct a tree hierarchy as in Figure III-38. Traditional wheels are mounted onto a hub, which is normally connected to rotors and the brake calipers. Unsprung elements include components that are not connected to the body, but are essentially in contact with the road surface. In this tree, the wheel assembly is a 5th level component as a subset of the braking branch. This syntax tree is flexible at the lower levels of the tree. Wheels can easily be swapped out, as well as braking components. But as we travel up the tree it is much more difficult to switch suspensions without massive expense and engineering effort.

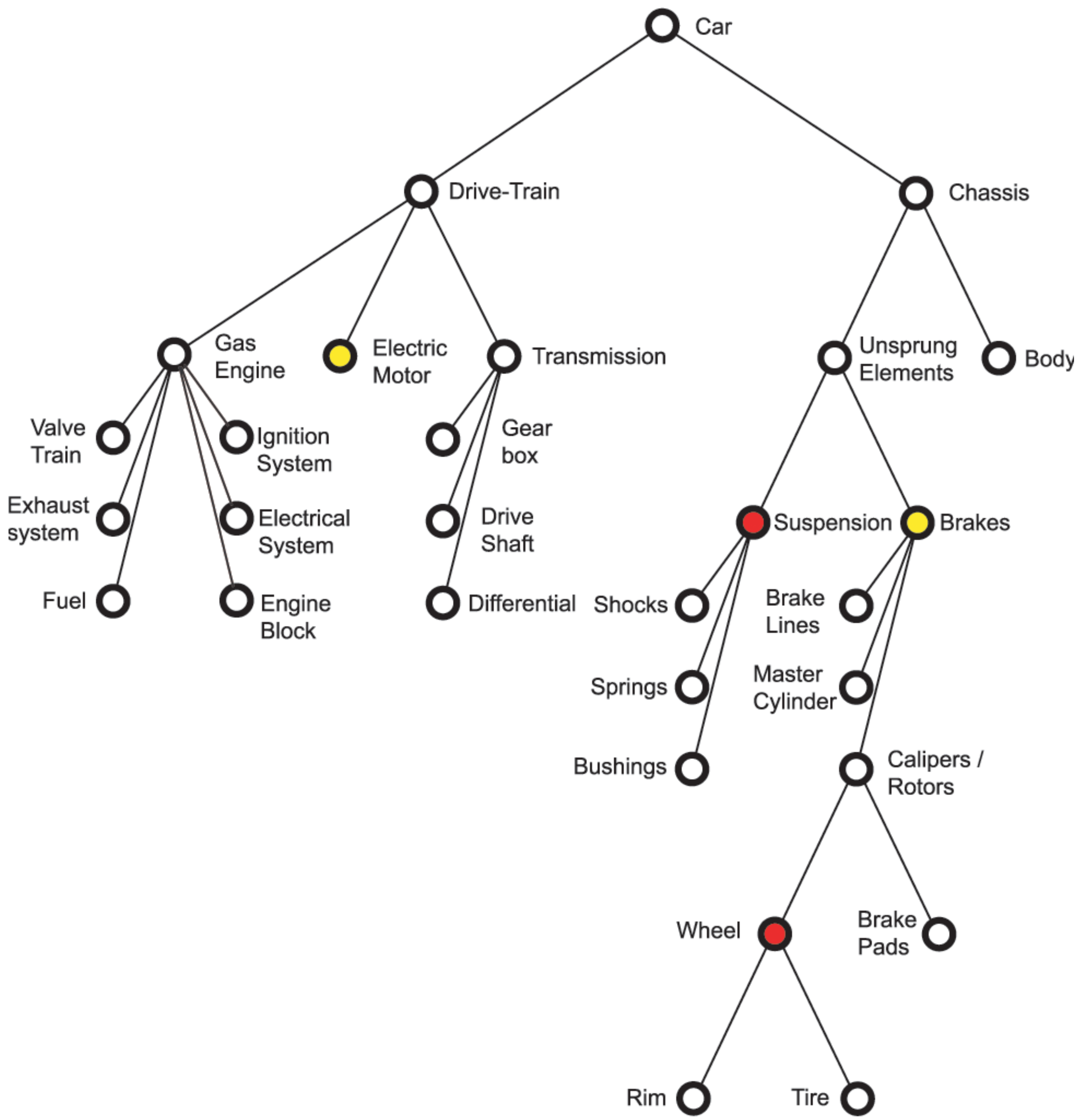

Figure III-38: Wheel syntax tree

B. Abstraction and Interfaces

Wheels (red node) are the principle contact surface between the vehicle and road. Conventional cars work because a propulsion system is located within the main body of the chassis where the transmission and drive train elements convey and convert thermal energy into usable rotational movement. Much of that energy is lost from the engine to the wheels. In a hybrid propulsion system, an **electric motor** (yellow node) drives the vehicle at low speeds because the motor is more efficient than a gas engine in this state. The gasoline motor helps to charge the battery and is the primary propulsion system at higher speeds. Hybrid systems benefit from regenerative **braking** (yellow node) because the electric motor can harness energy that would otherwise be lost to the heat generated during braking. Identifying these key functions is the first step in the abstraction process. In Figure III-38, the red and yellow nodes key in the branch connection points for abstraction and then innovation.

A closer examination of the interfaces helps to add another identifying layer of elements that can enrich this step. Brakes and tires are intimately connected by similar geometries and the connecting element is the **suspension** (red) system. Both systems work in parallel in order to provide proper ride dynamics. Suspensions are limited to several configurations because they connect the wheels and brakes to the chassis. Rethinking suspension systems can be initiated by recombining the nodes in question.

C. Standardized interfaces, substitution, and replacement rules

In comparison, the seat grammar combines four elements, but the key difference with the motor wheel is the geometric location of the candidate components. The motor design calls for the combination of the braking and suspension elements using the electric motor as the key-connecting datum. Figure III-39 shows a CATIA 3D model of the proposed design. Figure III-40 shows how the electric motor would connect to the chassis. By directly powering the wheels with electric motors at the wheel itself, we have replaced the traditional transmission and drive train. The wheel motor becomes a self-contained mobile element which easily could be standardized, highly optimized and eventually become a car building block.

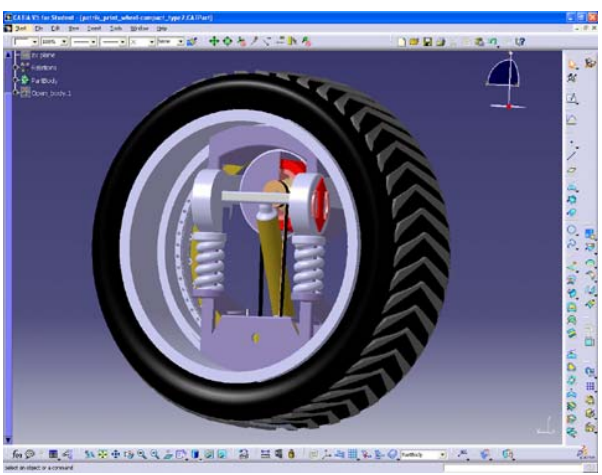

Figure III-39: 3D Catia Model of the motor wheel

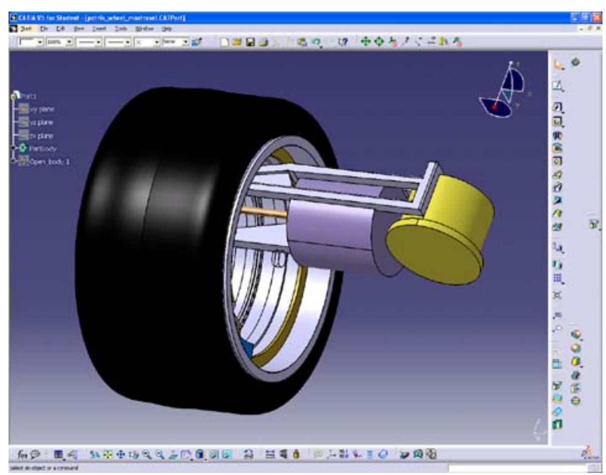

Figure III-40: 3D Model of the electric motor wheel

The new syntax tree is illustrated in Figure III-41. The area dotted in blue represents the motor wheel design. This radical reconfiguring has transformed a 5^{th} level component to a second level component. The most significant high-level change is the electric motor has jumped from the drive-train branch to the chassis branch and into the unsprung elements subsystem.

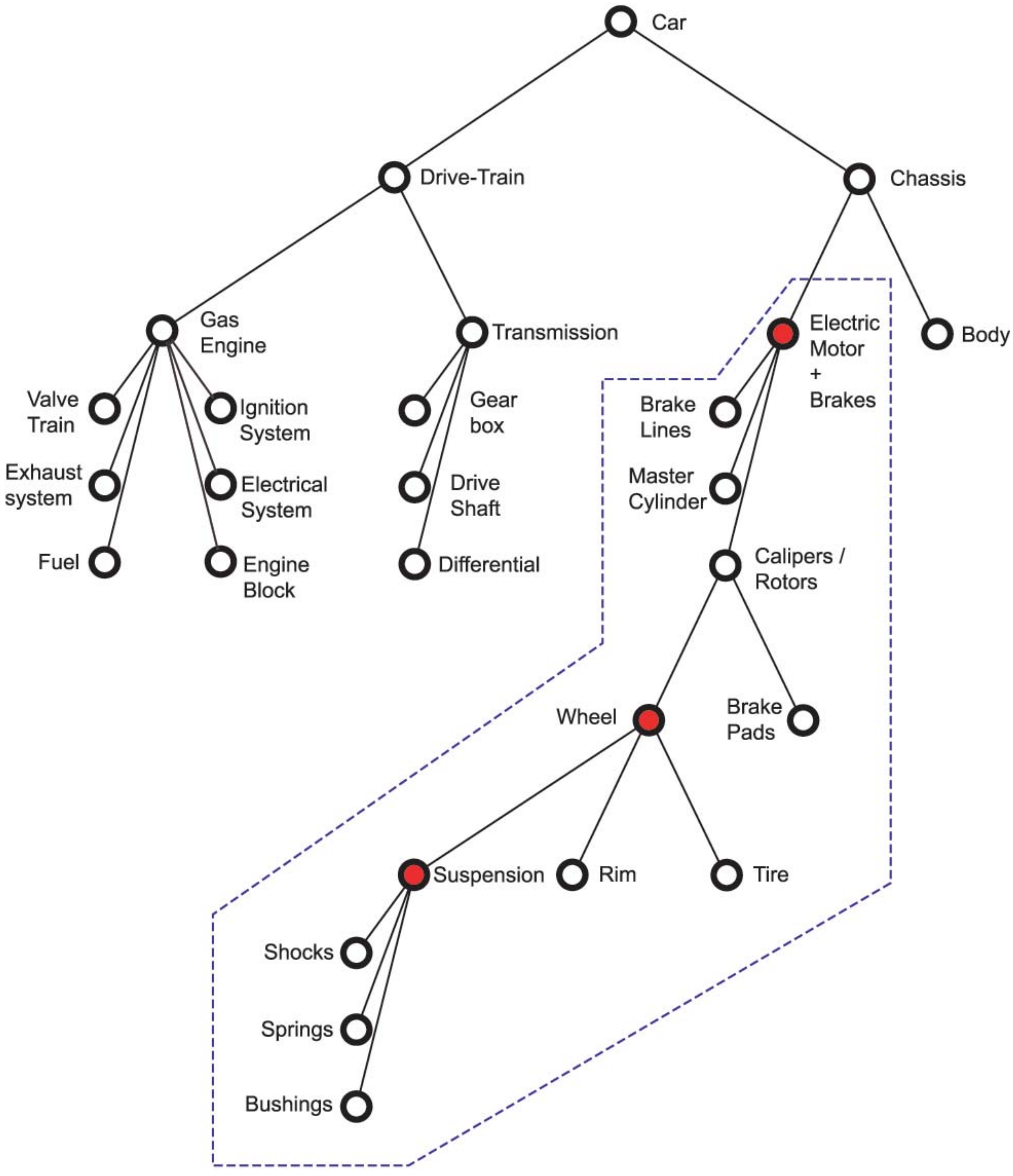

Figure III-41: Hubless wheel with embedded suspension and electric motor syntax tree

D. Fabrication, assembly, and supply chains

Similar to the seat grammar, the motor wheel challenges traditional supply chains but improves assembly and fabrication constraints. Figure III-42 shows an alternative parsing of the motor wheel grammar. Each parsing has dramatic implications in design integration. Because so many components need to be packaged into such a small area, the dominating constraints are compliant geometry and wheel travel distance, thus the introduction of the hubless rim.

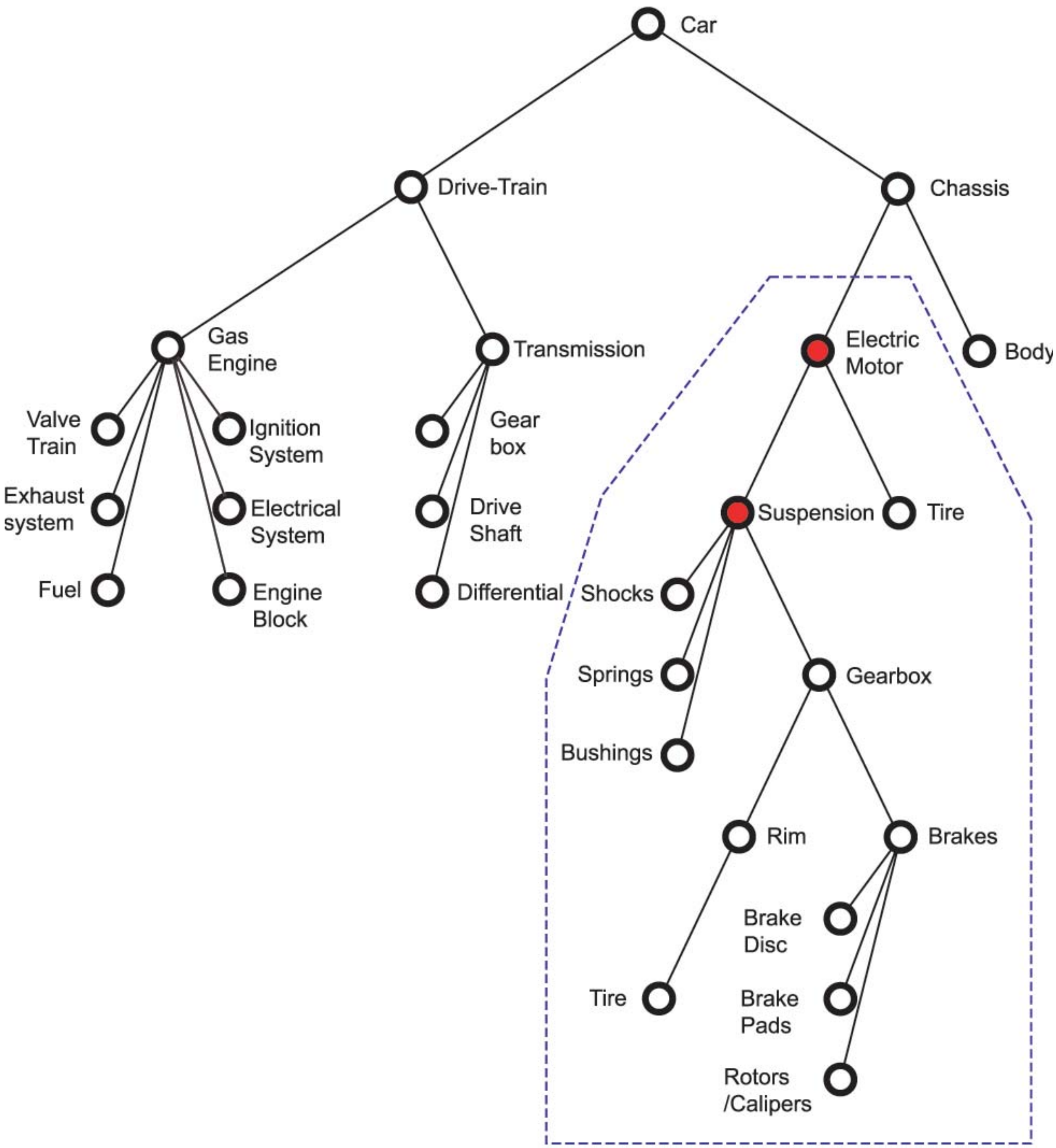

Figure III-42: Alternative Hubless wheel with embedded suspension and electric motor syntax tree

The empty center of the wheel assembly provides the necessary space to fit all the components, however we sacrifice the structural integrity of the rim. In response, the gearbox, which transfers the power to the wheels, requires a rail to connect to the rim, thus giving us the opportunity to reinforce the hubless rim.

3D prints help visualize the key aspects of any design. Figure III-43 shows how the suspension would work given a change in road conditions. The electric motor remains at a constant level with the chassis while the suspension and gearbox make up the travel distance.

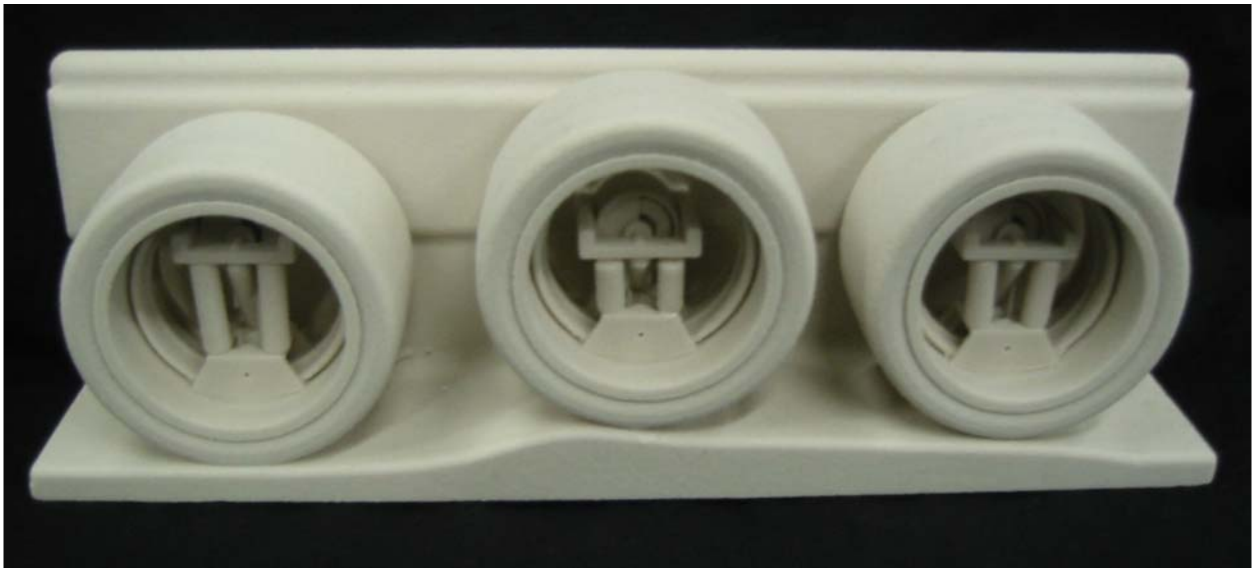

Figure III-43: 3D print shows the suspension travel at work

E. Product grammars specify languages of designs (William J. Mitchell in italics)

Again, let us examine Mitchell's product grammar methodology:

1. A starting component. This may be a low-level part that provides a convenient starting point for building up an assembly, or it might be a high-level organizational diagram, consisting of construction lines, etc, that provides an abstract framework to guide the design.

Begin with the wheel. Parse the wheel into its basic elements. Construct the syntax tree.

2. A vocabulary of elementary components.

The rim and the tire are the basic elements. Other basic elements also include springs, struts, rotors, motors, calipers, etc.

3. A set of sub-assembly replacement rules.

Integrate elements to produce a more synthesized syntax tree. Substitute the transmission by placing the electric motor at the wheel. Combine the braking system with the suspension by using the electric motor as a structural element.

Designs in the language specified by the grammar are derived by recursive application of the replacement rules to the starting component.

Recursive application yields new design solutions and new paths for exploration. In the case of the seating grammar, new ways of getting in and out provide structural safety opportunities by combining the horizontal support surface with the door. The motor wheel grammar also shows signs of emergent design behaviors. Figure III-44 shows traditional and innovative connections between the wheel and chassis. Conventional suspensions take up a significant amount of space and can only be connected in one direction. Because of the radical combining of traditionally separate elements, the design team is presented with the opportunity to connect to the chassis in many different ways. Using the electric motor as a structural connector, we can replace the connecting points with a rotational pivot which can allow for omni-directional movement, thus changing the way cars travel and park.

Figure III-44: 3D print different connecting options

5. EXAMPLE 3: A NEW ARCHITECTURE FOR THE CAR

Given the developments in the product grammar methodology sited in the pencil, seat, and motor-wheel examples, let us apply the same strategy for an entire vehicle. Complete automotive assemblies are complex and extremely sophisticated. They have evolved for over one hundred years. During that time, the number of systems on the vehicle has increase dramatically with the advent of electronics and safety systems. Because the number of components have increased, the original equipment manufacturers (OEMs) have distributed more of the innovation out to suppliers. The increased number of participants forces the industry to the carefully coordinate assembly. However, innovation is then compartmentalized in many cases because the supply chain demands it.

This section explores a new car grammar by exploring two new architectural definitions of the grammar. We begin by examining the parsing of a conventional car assembly, and then apply the rules of the grammar to establish a new architecture. As in all design practice, that which is learned from case studies adds to our formalization of this set of methods.

A. Parsing of Products

Begin with a conventional assembly and parse the syntax tree into its constituent branches in Figure III-45. This diagram shows the typical distribution of automotive components. Many variations of this syntax exist, but let us start with this baseline. The top 2 levels including drive-train (gas engine, electric motor, transmission) and the chassis (body and unsprung elements) fall under the close guidance of the OEMs because of branding and assembly factors. However, all levels below that fall under the domain of many suppliers with the exception of body panels and glazing. A radical reconfiguring of this tree changes the rules of manufacture and has great implications towards design.

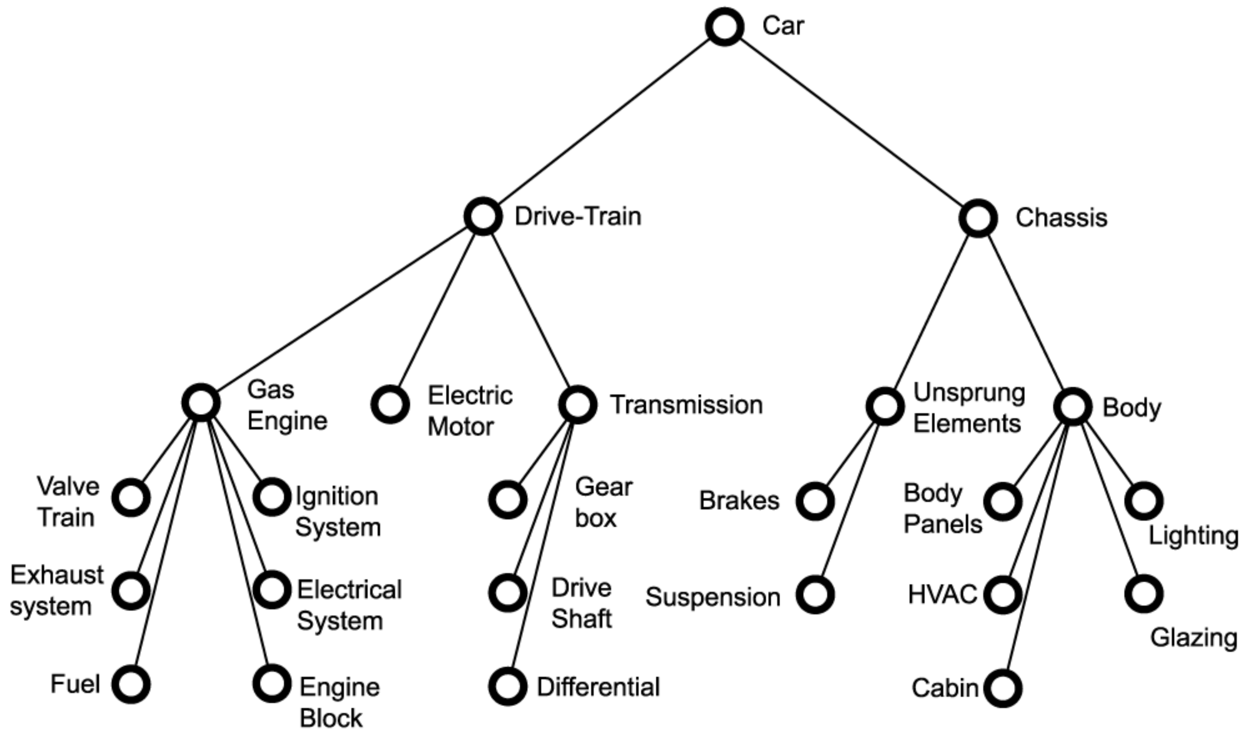

Figure III-45: Conventional car syntax tree

B. Abstraction and Interfaces

A comparative study of car typologies is helpful in understanding and therefore abstracting the key architectural subdivisions for the car grammar. Figure III-46 maps 6 different vehicle types and begins to extract the essential commonalties between each category. We discover that all vehicles have an exterior skin that wraps the assembly, thus creating an envelope; a passenger compartment containing the occupants and controls, a system of support and services which includes all the electro-mechanical components to support the driving experience; and finally the storage which houses either deliverables or fuel payload. Figure III-47, presents a color code that separates each of these subdivisions in order to study them further. During our product grammar investigation in MAS 968, William J. Mitchell writes:

> An architecture is a spatial grouping and hierarchical nesting of functions that takes account not only of fundamental functional logic but also materials and fabrication, assembly, supply chain organization, and desired visual and spatial character.
>
> An architecture is far from neutral. In fact, establishing an architecture is probably the most important step in the entire design process.
>
> An architecture can be described (particularly at the top levels) in an abstract, diagram – much as a building design might develop from a parti.
>
> An architecture provides a framework for generating useful variants by substitution and parametric variation. It is the starting point for specifying a language by means of a grammar.[5]

[5] Mitchell, William J., "Product Grammars 5: Defining an Architecture," March 3, 2004

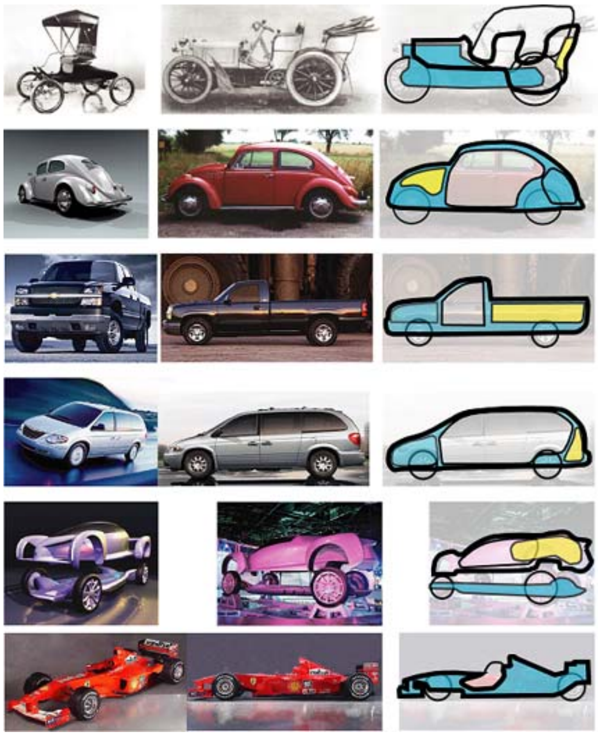

Figure III-46: Typological study

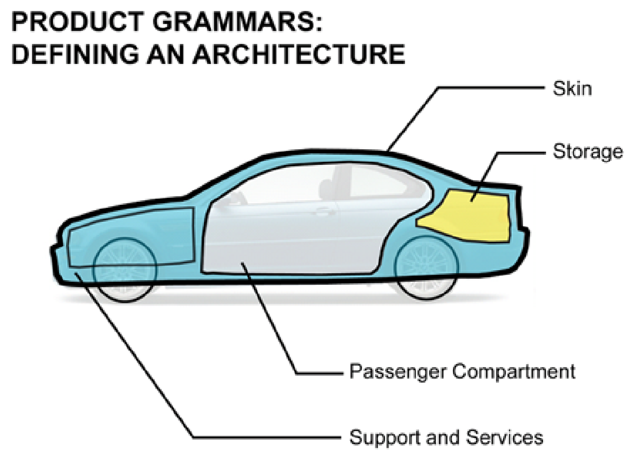

Figure III-47: Defining a product grammar architecture

After defining this architecture we can write a syntax tree as shown in Figure III-48. This division allows us to examine each assembly branch by describing the desired functionality and then matching those functions with precedent studies.

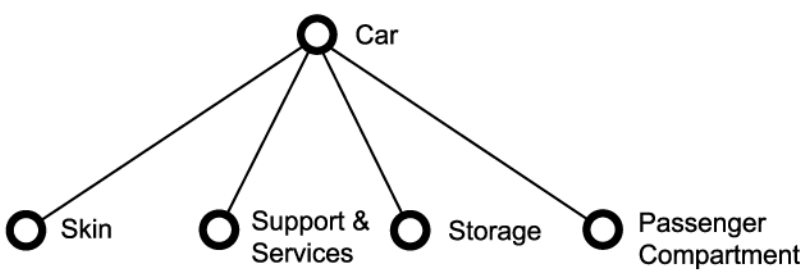

Figure III-48: New car syntax tree

C. Standardized interfaces, substitution, and replacement rules

Figure III-49 describes the desired characteristics for each subcomponent. Creating descriptions allow for the examination of existing products and their mapping onto the syntax tree, thus separating the form of the product and its functionality.

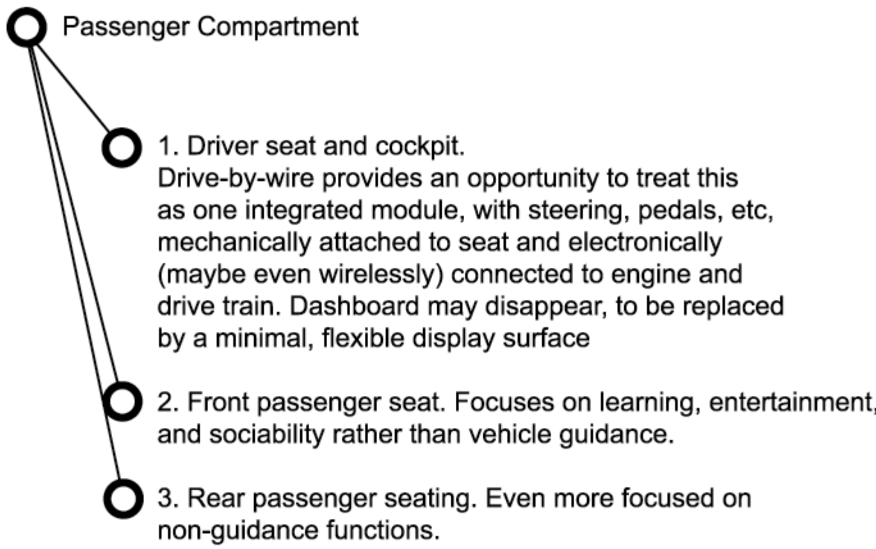

Figure III-49: Passenger Compartment component descriptions

This study augments previous mapping studies like the interior seating configuration because it places a hierarchical structure to the investigation. Now, the interior solution space can integrate the differences between the driver's seat and the remaining seats for passengers. We also redefine the interface between the driver and the propulsion system by introducing a Drive-by-Wire assumption to the grammar. Drive-by-Wire systems remove the need to have mechanical linkages to the engine compartment like traditional steering columns, thus changing the parametric constraints normally applied to interface design and geometric location of the driver's seat. Figure III-50 illustrates some of the precedents found during these investigations in MAS968.

Figure III-50: Passenger Compartment precedent study

Clumping together support and services radically changes assembly norms because systems like the suspension and the interior climate control that do not normally have much interaction now have a new grouping set. Ultimately, support and services systems do not have any aesthetic implications because they are hidden from the passenger and those outside the vehicle underneath design/styling surfaces like body panels and dashboards. However, by recombining these functions we can now rethink the relationship between expression and functionality in each sublevel of the syntax tree.

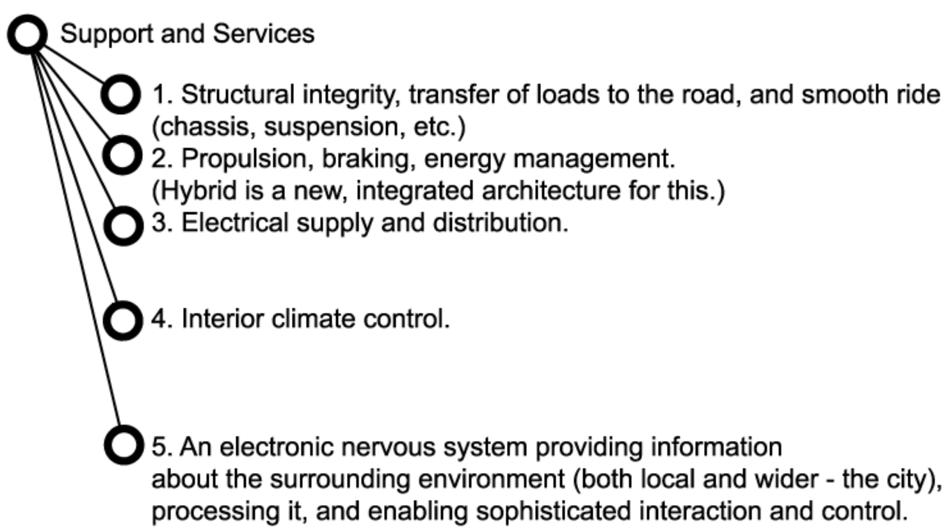

Figure III-51: Support and Services component descriptions

Figure III-51 diagrams each component and describes the desired functionally. Setting up the question while defining the product grammar is an important step, just like establishing the program in building design. In many cases, functionality can be augmented to the equation, thus allowing for new synergies. Figure III-52 shows the variety of precedent studies that can be substituted or modified to fit within the product structure. Professor John Heywood, of the Sloan Automotive Lab, said during one of his interactions with our research, “Let’s focus on innovating in those areas in which we are experts. Creative use of standard, highly optimized components is key, since we can not reinvent every single bolt in the design.”

Support and Services

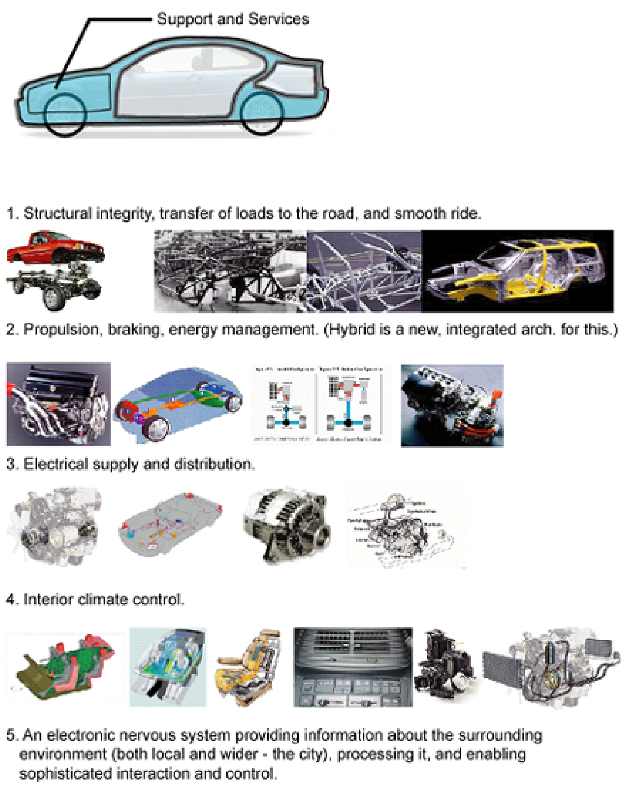

Figure III-52: Support and services precedent study

The skin is subdivided into distinct characteristics (Figure III-53) as follows: (1) Non-Operable skin, panels that aid in the aerodynamics and are part of the overall envelope of the vehicle; (2) Operable panels that aid in the ingress/egress (ie., doors); (3) vision systems that aid the driver by either analog or digital means; and a final layer, (4) a sensor-embedded, smart, display skin surface. The emergence of new display technologies like Eink and OLEDs presents a new dimension to skins, therefore creating a new branch is an otherwise traditional division of skins. The opportunity to fuse these branches together creates a newly combined functional aesthetic. Again, an industry as mature as the automotive industry allows us to draw upon the many investigations already in place, as illustrated in Figure III-54.

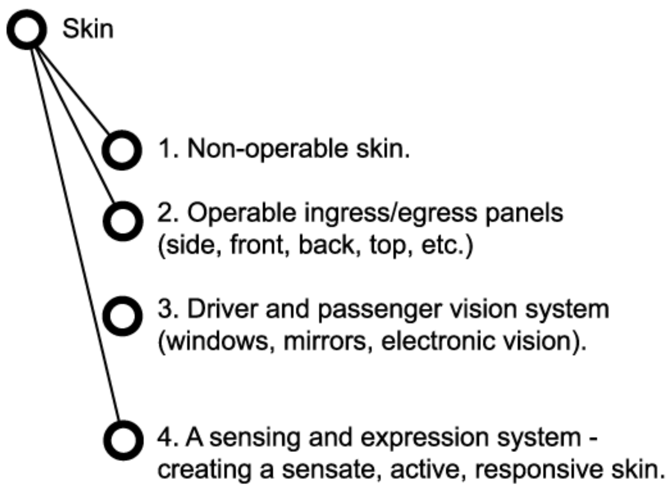

Figure III-53: Skin component descriptions

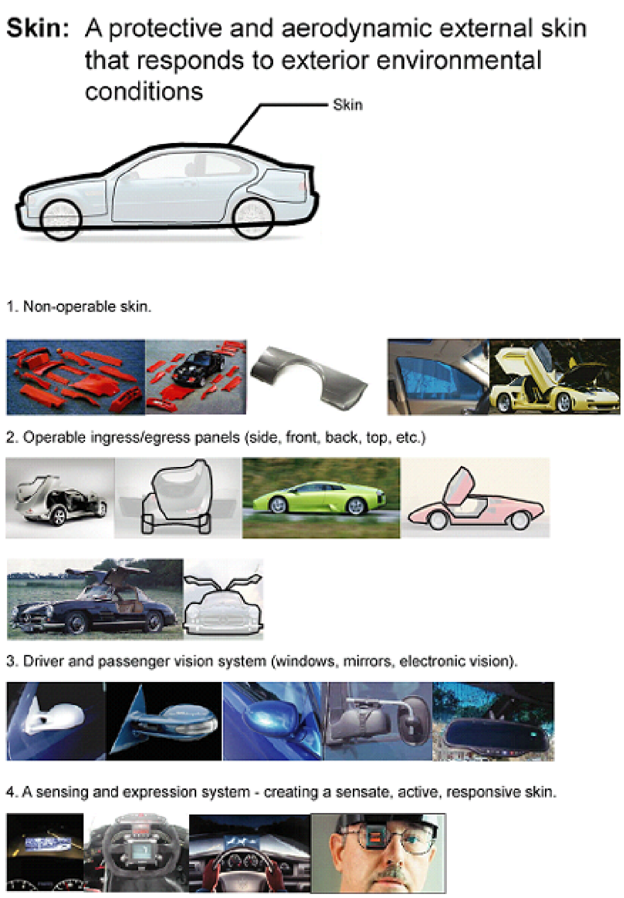

Figure III-54: Skin precedent study

Storage is categorized as the volume of accessible space in which payload is placed. Often it is a secondary consideration in design processes because of its perceived low priority. However, many OEMs have designed storage around a small number of common personal belongs like standard luggage sizes, golf bags, skis, and boxes. Figure III-54 & 55 diagrams the different possible storage typologies and their respective precedent studies.

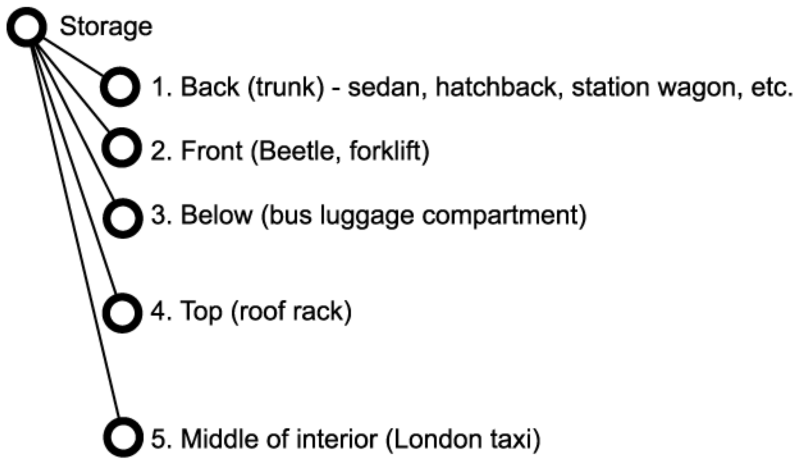

Figure III-55: Storage component descriptions

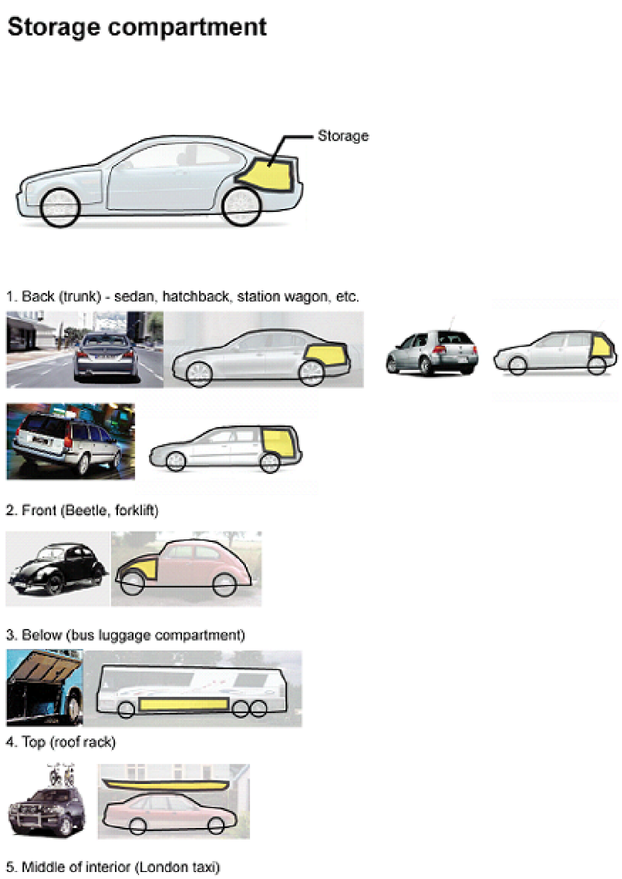

Figure III-56: Storage precedent study

D. Fabrication, assembly, and supply chains

After mapping the product architecture and evaluating the fabrication and assembly sequences, the decision was made to produce another car syntax tree that takes advantage of some of the previous grammar studies like the motor wheel and seat. The difficulty in the previous configuration is that the product architecture placed too much integration into support and services while ignoring the connecting points and interfaces between elements like the skin and passenger compartment. Figure III-57 shows an alternative car syntax tree that relies on a closer high-level subdivision than before.

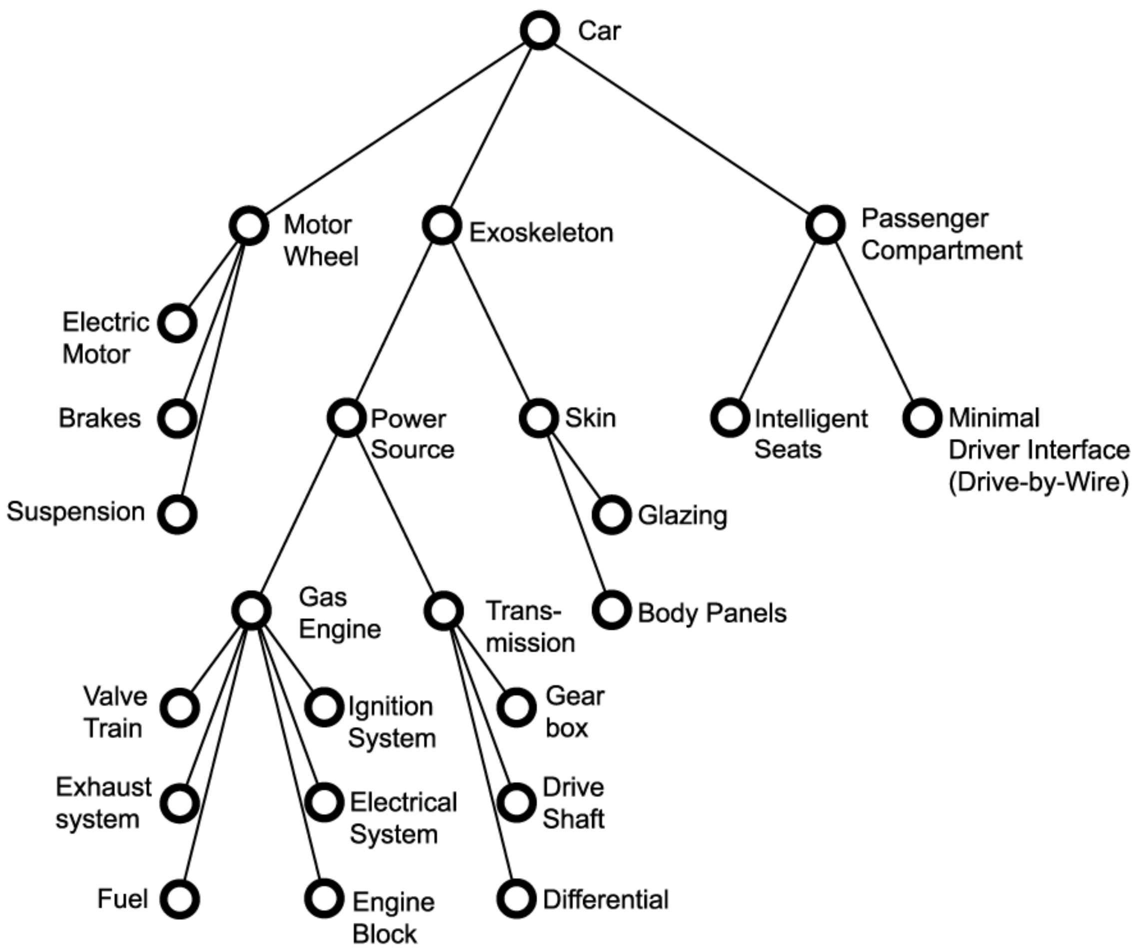

Figure III-57: Final car syntax tree

The above diagram reflects the Concept Car design with GM and Frank O. Gehry which was completed as of the summer of 2004. As the project develops this diagram will be developed and further refined as elements become more clearly defined and the workings of the system reflect use, fabrication, and assembly sequences. By relying on an exoskeleton similar to that of many motorcycles, it becomes our equivalent of a chassis. The separation of the passenger compartment allows for a very highly modularized and mass-customizable interior. Additionally, the connection points between the exoskeleton and passenger compartment can take advantage of new research in structural damping systems. The motor-wheels become a high level branch in the product architecture, because they now are self-contained propulsion units that are swappable. This modularization allows for the optimization of this module and the interface can be digitally mediated.

The following is an excerpt out of the “Gehry Car proposal” written by William J. Mitchell, with illustrations done by Mitchell Joachim.

Key Architectural Principles[6]

In many types of consumer products, exciting new design freedom emerges when traditional mechanical connections among components are replaced by flows of digital data. Cameras, for example, could take on a multitude of new and surprising forms when the traditional film transport mechanism was replaced by solid-state electronic components. The most innovative digital cameras now bear little resemblance to their film-based predecessors. The Gehry car will take similar advantage of advanced electronics to open up the possibility of new forms. In particular, it will utilize:

(1) Electrically powered, **digitally controlled wheels** in place of traditional engine and power train arrangements. This allows great freedom in locating the wheels relative to other major elements.

(2) **Drive-by-wire interface** (Figure III-58) in place of traditional steering column and dashboard arrangements. This allows radical reconfiguration of the cockpit, treatment of the passenger compartment as a module that can readily be separated from the rest of the car, and creation of a multimedia driving experience that intelligently integrates data streams from a wide variety of sources and presents them to the driver and passengers in a customized, context-sensitive way.

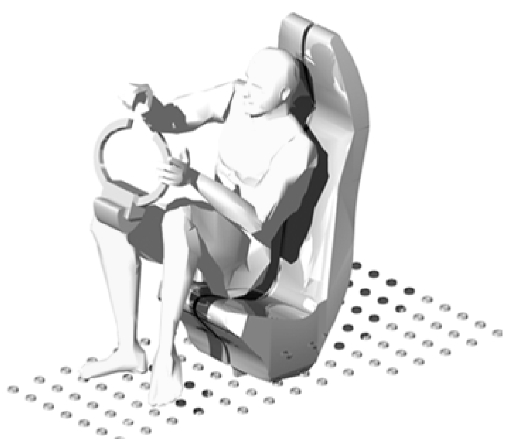

Figure III-58: Drive-by-Wire interface

Six Main Features of the Design[7]

Exploiting the potential of these principles leads to a highly modularized design composed of the following major elements:

(1) Electrically powered, independently controllable **wheels** (Figure III-59) with motor, suspension, brakes, and steering contained within each wheel assembly. Placing the suspension within the wheel itself is a significant innovation, and promises some important advantages. Each wheel has only two inputs: electrical power and digital data.

[6] Mitchell, William J., “The Gehry Car,” June 2004
[7] Ibid

Figure III-59: Motor wheels

(2) An **exoskeleton** (Figure III-60) that connects the wheels and supports the passenger cabin, storage units, and power source. This element can be optimized for structural efficiency, and (like the frame of a sophisticated bicycle) can become a major design feature.

Figure III-60: Exoskeleton

(3) A lightweight, technologically advanced **passenger compartment** (Figure III-61) suspended safely within the exoskeleton, like an egg protected within an egg carton. This compartment need not be fabricated from sheetmetal and glass. It can exploit the possibilities of advanced materials and embedded electronics to provide high levels of visibility, safety, climate control, lighting, sensing capability, and interior displays. And it provides an opportunity to break away from the familiar automobile aesthetic of painted sheetmetal.

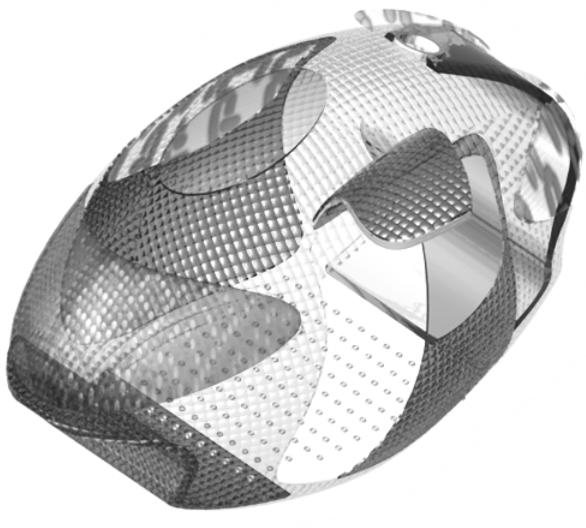

Figure III-61: Passenger Compartment

(4) **Intelligent seats**. These are highly articulated, intelligently controlled devices that intelligently embrace and release passengers for graceful ingress and egress, and provide the restraint functions traditionally handled by seat belts and airbags in an effective new way.

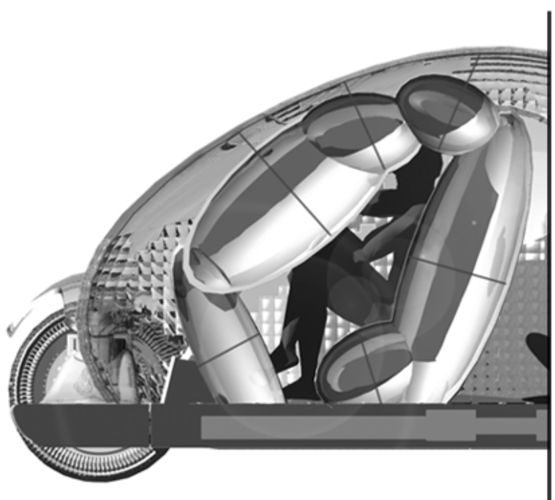

Figure III-62: Intelligent seats

(5) **Street smarts**. This car knows its city as well as a good London taxi driver does, and provides its passengers with an intelligent interface to the resources of the city. It accomplishes this through a combination of navigation system and database technology, sensing and learning as it traverses the city, and wireless network connection to servers and other cars. This intelligence is integrated, in context-sensitive fashion, into the drive-by-wire interface.

(6) The **power source** provides electricity to the wheel motors. It is attached to the exoskeleton, and has a high level of structural independence from the passenger compartment. Depending upon the performance and cost requirements, and the advantages and disadvantages of currently

available technology, it might be a gasoline/electric hybrid, a hydrogen fuel cell, or an advanced battery pack.

E. Product grammars specify languages of designs (William J. Mitchell in italics)

The language specified by this product grammar allows for exploration in each subdivision without loss of integration. For example, the exoskeleton group can explore many different configurations by isolating its branch of the syntax tree and keeping certain assumptions such as that the motor wheel will provide the propulsion at convenient connection points. Each division can do the same as long as the possible interfaces are defined and the structural hierarchy is kept flexible enough to accept added innovative characteristics like added functionality, a new aesthetic expression, or structural benefits.

Again, let us examine Mitchell's product grammar methodology:

1. A starting component. This may be a low-level part that provides a convenient starting point for building up an assembly, or it might be a high-level organizational diagram, consisting of construction lines, etc, that provides an abstract framework to guide the design.

The components include exoskeleton, motor-wheels, and the passenger compartment. This tree-level branch then includes the second-level tier of components like intelligent seats, new driver interfaces, suspension systems, electric motors, etc.

2. A vocabulary of elementary components.

The elementary elements are refined by functional descriptions and mapping of precedent studies.

3. A set of sub-assembly replacement rules.

Rapid changes begin with substitution of components at almost every level of the tree. Intelligent seats can be replaced with analog seats, smart skins with non-operable panels, driver interfaces are programmable therefore replaceable by customized driver preferences. The spatial freedom given by said configurations allows the designer to place value on the functionality of specific components and have them affect the form-making process.

IV. CONCLUSION

The design of automobiles poses challenges to designers and engineers because of the number and sophistication of systems and subsystems. Often design becomes compartmentalized into smaller design segments, thus challenging integration and overall unity. Developing a product grammar that encapsulates the key design concerns for a concept car is an opportunity not only to design a vehicle but to also apply this design methodology to products such as personal electronics, apparel, furniture, and intelligent skins. The product grammar applies also to the field of architectural design because of the need to synthesize structure, program elements, HVAC, lighting, and other key systems into one design statement.

The references used through this thesis reinforce the need to continue research in this area. Mature industries like the automotive industry have many challenges ahead because their systems have become highly optimized, thus squeezing out innovation. The process of thinking about product grammars dictates a high-level architectural reconfiguration of componentry, thus suggesting changes to refined manufacturing processes and supply chain linkages. These changes, however, provide the opportunity to rethink the ever-decentralizing nature of product development. Innovation is a cyclic process brought forward by both scientific discovery and economic forces. Another force that is often forgotten is the need for designers and engineers to reclaim areas of expertise and integration. In the building industry, architects, engineers, and contractors have become more and more specialized, such that the term “master builder” is no longer viable. Using innovative design tools and technologies is one way to re-integrate these separate entities. However, the changes must also be cultural. Both the automotive and architectural industries have mature and ingrained organizational practices which have evolved and have been optimized to that given structure. The key to refining design practice is the development of robust and flexible design and engineering methods.

The product grammar can be applied at a number of different scales and levels of complexity. The pencil, seat, motor-wheel and car examples cited in the product grammar chapter become progressively larger in scale and more complex. As tools become more sophisticated, the research in the use of the tools also needs to grow and to accommodate changing needs. Collaborative environments like the MIT Media Lab foster projects that are inclusive of differing points of view to inform the process of design. Building systems and new design methodologies that accept these different perspectives and compute innovative solutions are crucial and exciting areas of study made possible by design inquiry.

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