Modeling Design Changes in Vehicle Assembly Systems: Platform Transition Strategies and Manufacturing Flexibility

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Abstract

Driven by rising environmental and geopolitical concerns, regulations have been put in place over the last decade to compel car makers to lower the CO₂ emissions of their cars. Due to these increasingly stringent vehicle efficiency standards, considerable effort has been expended to reduce vehicle fuel consumption. Since the mass of the vehicle dominates all of these efforts, it can be argued that future emission requirements will be impossible to achieve with steel vehicle structures. A transition to lightweight, non-steel materials seems inevitable. However, non-steel materials in most cases require dedicated manufacturing systems due to specific manufacturing requirements. Thus, lightweight vehicle systems will require a distinct divergence between today’s manufacturing environment and the potential future manufacturing system.

While many studies have assessed greenfield production costs for conventional vehicles and the lightweight alternative, this research recognizes an important reality of the automobile marketplace: any future lightweight vehicle will be implemented out of a steel-based manufacturing environment. Carmakers will have to adapt existing plant infrastructure to the particular requirements of the non-ferrous material. This research develops a conceptual framework and a transition cost model to quantify change penalties of transition processes imposed on vehicle assembly systems. This transition model is applied to a case study provided by Ford Motor Company in order to better understand implications of different manufacturing strategies on the system’s capability of switching materials.

The research identifies three different manufacturing change penalties which have to be paid when switching the base material in vehicle assembly systems. Taking these penalties into account, case studies suggest when, to what extent, and how materials transitions can be realized most cost-effectively. Partial component-wise transitions are presented as an attractive alternative to full material transitions. Finally, strategies are proposed how to increase the material flexibility of automotive manufacturing systems.

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Chapter 1 – Introduction

The research presented in this thesis is an attempt to better understand how the difference in production cost between lightweight bodies and conventional steel bodies is affected by the specific transition strategy towards lightweight materials, the choice of manufacturing strategies in different periods, and the characteristics of both vehicle designs. Results are used to motivate a transition cost modeling approach for comparing cost of weight reduction strategies.

1.1 Motivation

In 2013, NREL’s Transportation Energy Futures Project found that the transportation sector accounted for 71% of total U.S petroleum consumption and 33% of total greenhouse gas emissions (NREL, 2013). Although fuel cost rise, the automotive industry’s intrinsic motivation to reduce fuel consumption is limited. The slightly higher attractiveness and sales price of an efficient vehicle does not in most cases justify the higher capital and operation cost which result from the need of more expensive production techniques and raw materials (Turrentine & Kurani, 2007). In the case of the premium segment, where sales prices might be sufficiently high to afford advanced material concepts, an improved efficiency was mostly used to realize a higher performance rather than a lower fuel consumption (Bandivadekar et al., 2008).

Driven by rising environmental and geopolitical concerns, regulations have been put in place over the last decade to compel car makers to lower the CO₂ emissions of their cars (Fig. 1). Due to these increasingly stringent vehicle efficiency standards, considerable effort has been expended to reduce vehicle fuel consumption, e.g. through improved start-stop-systems, downsizing, or more efficient powertrains (Bandivadekar et al., 2008).

However, it is the mass of the vehicle that dominates all of these efforts (McKinsey, 2012: 12). Stated improvements in fuel consumption vary between 4.5% and 8.0% for every 10% reduction in vehicle weight (Bandivadekar et al., 2008). To date, vehicle mass reduction has been accomplished through changes in vehicle geometry, while the material has largely remained steel (Ashley, 2013). Steel has always been the dominant material in automotive construction because of low cost and high performance – particularly in terms of strength,
stiffness, and formability (Davies, 2012). Moreover, the materials processing of steel, both in terms of shaping and assembly, is well-suited to the economics of mass production, which advantages processes with short cycle times. However, it is reasonable to assume that future emission requirements will be impossible to achieve with steel vehicle structures (KPMG, 2012). Thus, the transition to lightweight non-steel materials has been discussed as an effective way to decrease fuel consumption while leaving public and private mobility unaffected (Cheah, 2010).

![Figure 1. Fuel economy standard for passenger vehicles (C2ES, 2013; U.S. DOT, 2011).](image)

Notes (according to C2ES, 2013):
2. DOT sets truck standard to max feasible (1979-1996)
4. DOT sets car standard to 27.5 mpg (1990-2010)
5. Congress freezes truck standards at 20.7 mpg (1997-2001)
7. EISA changes CAFE to footprint standard (2008-present)
8. Obama Administration issues new car & truck standards (2012-2016)
1.2 Lightweight Materials

Many studies have assessed the cost premium that has to be paid for weight reductions; some examine material options throughout the vehicle (Davies, 2012: 87-90; Kang, 1998; Roth, Clark, & Kelkar, 2001; Shaw & Roth, 2002) and others focus on mass reduction strategies for particular vehicle subsystems, such as the front end (Roth, 2006). Based on MIT’s report “On the Road in 2035” (Bandivadekar et al., 2008), Cheah (2010) presented a comprehensive review of lightweight concepts which are summarized in Fig. 2. The range of weight reduction (between 16 kg and 653 kg) shows that any real effort to reduce weight will require designs reliant upon non-steel materials. The overview makes also clear that estimates of cost over total weight savings vary widely. One reason for the lack of consensus is that different studies propose different engineering solutions. Another might be that there is no clear guideline how to calculate the cost premium that must be paid for vehicle weight reduction. In most cases, studies use various methods to estimate the production cost for the common steel and alternative lightweight components and implicitly or explicitly subtract the one from the other. Subsequently, this cost premium is compared with the potential benefits from weight savings or the avoidance of governmental penalties.

Most investment for assembly facilities is spent for equipment and robots dedicated to particular vehicle geometry. This infrastructure is only able to perform certain operations required for specific joining methods (see chapter 2.5.2). The selection of possible joining methods depends on the parts’ material and overlap of those joining methods for different types of materials is rare. Thus, the transition to non-ferrous materials will necessarily require transition to a new range of vehicle production technologies.
1.3 Automotive Production Systems

Since 1913, when Henry Ford prepared the ground for assembly-line-based mass production (Duguay, Landry, & Pasin, 1997), the automotive industry has been one of the leading manufacturing industries in terms of productivity and production efficiency. The ‘lean production’ idea, which was identified and disseminated by the famous book The Machine That Changed the World (Womack, Jones, & Roos, 2007), further consolidated this leading position among manufacturing industries.

The high quantity of products and their technological complexity gives automotive manufacturing a unique nature in terms of both scale and complexity (Nieuwenhuis & Wells, 2003: 195). Carmakers are ambitious to increase production volumes in order to benefit from economies-of-scale, while, at the same time, improving processes and decreasing over-capacities. This leads to large-scale, complex, and fine-tuned engineering systems. These systems are tailored to the extent, quantity, and order of operations they are built for.
Consequently, and in contrast to job shop production, modern automotive manufacturing systems allow for allocating resources to operations and thereby for realizing a high level of resource and capacity utilization.

The consequences of capital-intensive assembly processes are that it takes more capital and time to make changes once these tailored systems are in place. Redesigning or reprogramming assembly lines, e.g. in order to respond to product changes, means in most cases that the production has to be stopped or slowed down. It should be noted that carmakers make every effort to avoid downtime due to the capital-intensive cost structure. Reorganizing an assembly line often involves notable effort to instruct workers, adjust or reprogram machinery, and organize materials supply at the line. In general, changing automotive production systems is expensive.

At the same time, mass production has engendered a market demand for product novelty and innovation. Automakers have found that vehicle “refresh” is required to maintain market position. This tension between high capital cost and the need for equipment retooling and refresh has led automakers to consider strategies that can limit the capital costs of conversion from one vehicle design to the next (when using the same base material). The conventional strategies have centered upon expensive, high volume equipment that can be fitted with purpose-built tooling that can be changed with each vehicle revision. More recently, the introduction of programmable production equipment has afforded the automaker further opportunities to reuse and repurpose capital intensive equipment.

1.4 Transition Strategy

Today, the typical vehicle main structure – called Body-In-White\(^1\) (BIW) – is made of steel stampings and comprises about 64% steel (Ghassemieh, 2011: 373). As this type of design accounts for the great majority of cars produced in the world, nearly all existing vehicle manufacturing plants are set up to solely produce steel vehicles. Every new vehicle design is introduced in this existing steel-based manufacturing environment. However, non-steel materials require in most cases dedicated manufacturing systems due to different manufacturing requirements. Thus, there is a distinct divergence between today’s

\(^1\) Han and Clark (1995) presented a detailed discussion of the Body-In-White concept.
manufacturing environment and the potential future manufacturing system that can process lightweight non-steel materials. While automakers have a good idea of what technologies will be required, the economic consequences of that transition are imperfectly understood. Due to high cost and limited benefits, no automaker will introduce lightweight designs until it is absolutely necessary. However, it seems unlikely that a "step change" at the last minute is most efficient because of particularly high investment requirements and the necessary downtime to implement changes. In the case of an earlier transition, it does not make sense to build completely new production facilities for an innovative lightweight design, in the absence of high production rates. The consequence is that the production capacity required for an early introduction of a niche product needs to be realized in the existing infrastructure. Thus, transition strategies must recognize the realities of the automobile marketplace. Because the automobile market requires routine vehicle redesign, vehicle assembly plants are regularly redesigned to accommodate these model changes. These regular plant redesigns introduce an alternative to a step change; a transition period during which elements of necessary lightweight manufacturing can be introduced before they are required. The decision carmakers face is to adapt existing plant infrastructure either to the specifics of a new steel design or to the particular requirements of a lightweight alternative.

1.5 Transition Cost Modeling

It should be noted that the difference in investment cost required to prepare an existing manufacturing line for the production of a new steel design or of an innovative lightweight design has an impact on the difference in production cost per vehicle. Production costs per unit (i.e. per vehicle) include a variable portion and a fixed portion\(^2\) that is spent at the beginning of production, annuitized, and spread over the total production volume. Thus, the cost premium that has to be paid to produce a lightweight automotive design (and to realize weight reductions) depends not only on the difference in vehicle designs and variable production costs but also the history of the installed manufacturing system. The notion that unit costs of a vehicle are partly a function of the manufacturing infrastructure that was already in place before the vehicle is introduced is called path dependency for the remainder

\(^2\) For an automotive assembly plant, fixed costs are mainly composed of cost for tooling, joining equipment and building cost.
of this work. The term emphasizes that current unit cost depend on the path that was taken to reach the current manufacturing state.

In order to analyze the path dependency of production cost for lightweight vehicles, a *bitemporal* transition cost model was developed (Fig. 3). It contains two major components, a spreadsheet-based Process-Based Cost Model (PBCM) and a Transition Cost Module based on Visual Basic for Applications (VBA). The process-based cost modeling strategy promoted by MIT’s Materials Systems Laboratory attempts to relate process requirements to product cost. For a detailed discussion of process-based cost modeling see work presented by Kirchain, Field, and Roth (Field, Kirchain, & Roth, 2007; Kirchain & Field, 2001).

Different components of the PBCM take as input task-specific parameters (e.g. number of connects, part count), operation-dependent parameters (e.g. number of shifts, working days per year), and financial inputs (e.g. equipment cost, factor prices). The process component calculates process requirements, such as cycle times and net production rates, that are needed to meet the proposed yearly production rate. The operations component takes them and calculates the amount of labor and physical capital that will be required under given operating conditions. In a next step, the financial component translates these resource requirements into cost. The model output is given in the form of overall material, labor, energy, equipment, tooling, and building costs, as well as intermediate process parameters. The PBCM model can be used to calculate production cost for a given manufacturing scenario.

The Transition Cost Module is set up to estimate the net costs that occur when switching from one (initial) manufacturing scenario to another (final) scenario over time. Transition costs include the money spent for new machinery or building area, as well as the salvage value of sold assets.

The module takes as input the complete set of output data from the PBCM for two different manufacturing scenarios. It outputs detailed cost tables and graphical illustrations of investment expenditures for the full transition process. Additionally, the net output rate

---

3 The system is modeled for two different scenarios at two different points in time. In a second step, the transition from the one to the other scenario is computed.
during the transition process is generated since a reorganization of the plant’s infrastructure leads to a disturbance of operation processes and a lower production volume.

Figure 3. Schematic plot of different cost model components (adjusted from Rivest, 2012).

Notes: The Process-Based Cost Model (PBCM) (Field et al., 2007; Kirchain & Field, 2001) consists of three different components – a process model, an operations model, and a financial model. Each component (except the process model) takes as input intensive data generated in the previous process step (“requirements”) and extensive data stated by the user (“conditions”). The financial model outputs production cost by assessing resource requirements under given financial conditions. The Transition Cost Module is loaded with data from all PBCM components for two different manufacturing scenarios (bitemporal modeling). By assessing the two different data sets with regard to the boundary conditions defined by the user, the module generates the investment required to switch from the initial manufacturing scenario to the final manufacturing scenario.

1.6 Framework

The analysis of manufacturing strategies is based on a case study developed in cooperation with Ford Motor Company. The company provided two different data sets – for a conventional vehicle and a lightweight vehicle. Many other input parameters for the cost
models were estimated based on data available from previous research projects in MIT’s Materials Systems Laboratory.

The purpose of this case study is twofold – (a) motivating a bitemporal transition cost modeling approach to calculate the cost premium for emission reduction strategies and (b) using this kind of cost calculation to better understand the implications of different manufacturing strategies on the system’s capability of switching materials:

(a) There are different ways to reduce fuel consumption and weight reduction is only one of them. As described in chapter 1.1, companies would not increase revenues if they could produce cars with a higher than required efficiency. Therefore, they are motivated to meet but not exceed required fuel economies as cost-efficiently as possible. With other things the same, a company would always select the strategy that allows for reducing emissions (CO$_2$) for the least additional cost possible ($). Figure 4 illustrates this relationship.

In order to develop a holistic strategy to reduce emissions, it is crucial for companies to understand how expensive different approaches can be. This is also the reason why every concept in literature to reduce emissions is labeled with a cost figure (e.g. $/Kg, $/L, $/gCO$_2$). These labels are in most cases based on a static cost assessment between two alternatives, often omitting the cost (or cost saving) of the actual transition to the new design. The case study developed with Ford is used to shed light on those transition cost and the path dependency of unit cost.

(b) This bitemporal approach is applied to compare different transition strategies for various boundary conditions and design assumptions. Strategic part sharing is generally seen as an approach to increase manufacturing flexibility and decrease production cost. It has implications for material transition capabilities. Also the similarity of initial and final design affects transition cost. The greater the difference between the manufacturing requirements of two designs, the more costly is it to switch.

These and further relationships are explored in the search of a cost-efficient and effective guideline for automotive material transitions.
Figure 4. Schematic plot of different design strategies to reach the emission target.

Notes: As one strategy to reduce emissions becomes more expensive over time, a switch to another strategy might suddenly become cost effective. One example could be the trade-off between a more efficient drivetrain and a roof made of carbon-fiber. At the moment it is still cheaper to optimize the drivetrain than to introduce structures of carbon-fiber (see McKinsey, 2012) but this might change when the efficiency potential of the drivetrain is nearly fully exploited.
Chapter 2 – Automotive Assembly Systems

In order to recognize the benefits of transition cost modeling for the assessment of weight reduction strategies, it is necessary to understand relevant features of the manufacturing system (chapters 2.1–2.6) and the structural basis of the static process-cost modeling approach (chapter 2.7). Once this scope is defined, it is possible to assess the advantages and disadvantages of the modeling framework proposed in this study.

2.1 Manufacturing Flexibility

The ability of manufacturing systems to respond to changes in the environment has extensively been studied in the academic world. Reviews of relevant literature were presented by Sethi and Sethi (1990), Gerwin (1993), Toni and Tonchia (1998), Koste and Malhotra (1999), and De Toni and Tonchia (2005). Described by Wahab and Osman as the “ability of changing production effectively and rapidly responding to requirements” (Wahab & Osman, 2013; see also Benjaafar, 1994), manufacturing flexibility has become an important feature of manufacturing organizations. Based on an often cited listing presented by Browne et al. (1984), Sethi and Sethi (1990) described eleven different types of flexibilities. They further propose that these different types can be classified into three basic groups with decreasing granularity: Basic component flexibility, system flexibility, and aggregate flexibility.

The three types that lie within the scope of this study are product flexibility, volume flexibility, and process flexibility. Brown et al. (1984) provides the following definitions:

**Volume Flexibility:** “The ability to operate an FMS profitably at different production volumes”

**Process Flexibility:** “The ability to produce a given set of part types [...] in several ways”

**Product Flexibility:** “The ability to changeover to produce a new (set of) product(s) very economically and quickly”

It becomes clear that flexibility is a “complex, multi-dimensional and hard-to-capture concept” (Sethi & Sethi, 1990). In order to help decision-makers think about what kind of
flexibility is required and how to invest in it, many researchers have not only tried to structure the concept, but also describe the interdependencies between different types of flexibilities (Gupta & Goyal, 1992; L. L. Koste & Malhotra, 2000; Oke, 2013). Also, the relationship between process and product flexibility was assessed (Athey & Schmutzler, 1995). This led to the idea that resources could be invested in different manufacturing capabilities, making the manufacturing systems "flexible" with respect to a range of expected and unexpected scenarios (Fine & Freund, 1990; He, Chen, & Xu, 2011).

As this study attempts to better understand the implications of current and future manufacturing strategies on the cost premium for lightweight vehicles, it is important to point out that certain manufacturing strategies are chosen with the intention to reduce cost and increase flexibility. Flexibility is only advantageous if the conditions arise in which the flexibility's potential can be exploited. In this case, the carmaker has the option, but not the obligation to act or react. This ability to react has a value for the decision maker (compare with real option theory; Myers, 1977; Dixit & Pindyck, 1994) and can in most cases only be realized by paying a premium on upfront investment cost or by accepting higher variable cost. An assessment of cost alone does not capture the value of flexibility and might lead to faulty strategic decisions. Although the quantitative value of flexibility is not calculated in this study due to its stochastic nature, features of the transition to lightweight vehicles are qualitatively analyzed in the light of manufacturing flexibility.

2.2 Material Strategies

Lightweight high-performance steel, carbon-fiber sheets, and aluminum structures appear to be on the verge of becoming serious alternatives in automotive production. In 2013, the average passenger vehicle was still 75% of metal (Ashley, 2013) but with a decreasing fraction of ferrous steel and more aluminum and plastics in every new model.

The public discussion about alternative materials is sometimes misleading as it mostly focuses on single models. The problem of how to design or build vehicles using lightweight materials has rather been solved. The challenges carmakers face today concern the production system more than those associated with a single vehicle. How to introduce new materials into existing production infrastructure, how to reduce the risk of supply shocks, how to overcome sudden cost spikes – these are the questions industry attempts to solve. In
this study, capital costs that result from introducing new materials into existing manufacturing systems are called *material transition cost* or short transition cost.

Cost Modeling is attractive as basis for decision-making if empirical data is limited. This is certainly the case for the transition to lightweight materials. Since the early beginnings, steel was the primary material in automotive construction. Increasingly, other materials are seen as a serious option — mainly due to governmental regulations (Fig. 2). Most companies have not undertaken a wide-reaching changeover to other materials, so that practical knowledge of production with other materials is rare. Cost modeling might help decision-makers think about how to enable cost optimization in the future. A better understanding of life-cycle costs is critical since different lightweight strategies experience a serious competition. Every carmaker has its own expectations regarding future structural materials in automobile manufacturing.

In 2013, Volkswagen announced its intention to replace aluminum with high-strength steel to save weight and money. The company’s head of the Materials Research and Manufacturing department explained that “it is possible to reduce weight without the use for more costly materials such as aluminum and carbon fiber” (Schmitt, 2013). At the same time, BMW is betting on carbon-fiber as the material of the future by investing more than 137$ million in production facilities together with Germany’s SGL Carbon, a carbon-fiber producer BMW already purchased in 2009 (MarketWatch, 2014).

2.3 Sharing of Operations

This research focuses on automotive body assembly, the most automated area of production with a “degree of mechanization exceeding 95%” (BMW Group, 2013). While there are a few workers who load tools, transport parts between stations, or assemble them manually, the bulk of vehicle body assembly is conducted by robots that connect body parts by employing different joining methods such as spot welding or riveting. These robots are grouped in independent clusters along the process lines.

The assembly line is a typical mass-production system, heavily benefiting from the fact that each task is performed hundreds of thousands of times. However, the steady increase in product variety is accompanied by a drop in production rate, as well as total production volume. Carmakers have to handle more models in the same plants. This increase in product
variety led to the idea that resources could be shared among the production lines for different models. Omar (2011) describes this weakening of the original mass-production character as a shift from economies-of-scale to economies-of-scope (p.12). No matter how it is framed, all types of resource sharing have in common that average costs per unit are reduced by spreading fixed cost (for machinery, equipment, labor, etc.) over a higher production volume or, in fact, the combination of different production volumes.

The type of resource sharing studied the most in the automotive context is *platform sharing* and a nearly limitless number of authors have established frameworks how to think about it (for a review see Jiao, Simpson, & Siddique, 2007; Johnson & Kirchain, 2009). However, this well-defined concept is surrounded by looser interpretations of resource sharing.

Figure 5 illustrates the idea that platform sharing implies sharing of components and sharing of operations, and, additionally, requires an organizational framework. In this sense, platform sharing combines two potentially cost effective elements, so that there are also two different ways to look at it – in terms of components or operations. The picture is meant to illustrate that it is possible to share operations without carmakers necessarily managing it as platform sharing. Sharing of operations is the broader concept and is not as strictly defined as platform sharing.

Since this study focuses on the assembly system, the focus of further remarks and analyses is on operations rather than components but the graphic shows that this kind of limitation does not mean to exclude the concept of platform sharing from the analysis.

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4 A product platform has been defined as the "set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched" (Meyer & Lehnard, 1997: 7; see also Robertson & Ulrich, 1998). Unique components complementing the shared elements provide each model in the product family with unique functions. Product platforms allow reducing cost while addressing the demand for product variety.
Figure 5. Venn diagram illustrating the relationship between different types of resource sharing.

Notes: This Venn diagram pictures the idea that platform sharing (Meyer & Lehnerd, 1997; Robertson & Ulrich, 1998) requires an organizational framework and implies sharing of operations (the same operations are performed on components for different models) and components (the same components are used for different models). However, components and operations might also be shared among production lines in absence of a formal platform sharing approach.

The term “sharing of operations”\(^5\) is used in this study to describe the case of similar assembly operations performed on components of different models. Regardless of whether strict platform sharing is realized, sharing operations among production lines can potentially have two cost decreasing effects; firstly, equipment’s utilization rate may be increased\(^6\), and secondly, fixed costs per unit may be reduced. This is the case since identical resources, e.g. joining equipment, tooling, and labor, are used to assemble two different models and fixed costs of these resources are spread over more units. However, more resource sharing means also higher capital costs and increased cycle times. In sum, it has the potential to reduce cost, but it depends upon the conditions of its application.

Sharing of operations can be realized in two ways: (a) the components are in fact identical, show a high level of similarity, or have at least the same locators and fixtures; (b) flexible manufacturing systems (FMS) with non-dedicated equipment and tooling are used to handle variable part geometries (Sethi & Sethi, 1990). Moreover, there is a nearly infinite

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\(^5\) Sharing of operations also compromises the case of different operations performed by the same equipment on components for different models.

\(^6\) A higher utilization rate becomes also cost effective by reducing fixed cost per unit.
number of combinations between these two extremes, depending upon the technologies available. “Flexible” means in this context that joining equipment is to some extent capable of automatically adjusting its functions dependent on the component type that is processed next (Norman, 2002).

Figure 6 is a schematic illustration of such a sharing scenario. Non-shared (dedicated) stations only process components for one vehicle while shared (non-dedicated) stations are able to perform operations on components for two different vehicles.

![Figure 6. Sharing of joining equipment among assembly lines.](image)

Note: Two assembly lines fabricating two different vehicles (A and B) might share joining operations.

### 2.4 Sharing of Operations and Process Flexibility

In this study, sharing of operations is used to describe manufacturing resources which are simultaneously used in the assembly process of two different types of vehicles on parallel assembly lines. This is an attempt to capture the versatility of production capital as a measure of resource sharing. The notion of manufacturing versatility also relates the concept of sharing to the field of manufacturing flexibility (see chapter 2.1).

Process flexibility has been described as the ability “to build different types of products in the same manufacturing plant or on the same production line at the same time” (Jordan & Graves, 1991). Thus, sharing resources among production lines and the ability to produce different vehicles with the same resources directly reflect the system’s inherent level of process flexibility (Jordan & Graves, 1995). Resource sharing can be regarded as an approach to introduce process flexibility in an existing manufacturing system.

The impact of resource sharing on the system’s level of process flexibility is basis for its second notable benefit besides economies-of-scale. Resource sharing reduces the
vulnerability of firm production to uncertainty in demand. Jordan and Graves (1991) presented in their often-cited paper with the title “Principles of the Benefits of Manufacturing Process Flexibility” that process flexibility in the form of manufacturing versatility can lead to increased sales and utilization rates. The reason is that production capacities can easily be adjusted as demand changes. They introduce the idea of “chaining” and show that this configuration allows for realizing the greatest benefits (Jordan & Graves, 1991).

Manufacturing facilities (e.g. a joining station) are built with a certain inherent production capacity. If a machine is only able to produce one product, then its capacity \(0 \leq c \leq 100\) also limits the product’s total production volume \(0 \leq y \leq 100\). The product can only be sold up to the machines capacity, even if the demand is higher. In the case that two machines can both produce the same two products, the machines’ combined capacity \(0 \leq c_1 + c_2 \leq 200\) raises the limits on the products’ combined production volume \(0 \leq y_1 + y_2 \leq 200\). This gives a higher flexibility to scale both production volumes and makes it possible to satisfy demand above the capacity limitations of the single-product case.

As we did not specify any properties of the products, why is it important for this simple case study that both products are “different”? The answer is that machine versatility is essentially a way to take advantage of the differential market demands for two “different” products. In this sense, it is the equivalent of financial hedging in a manufacturing context. This means that the flexibility benefits of resource sharing for assembly facilities come from the fact that the demand for components used for different models is in most cases not perfectly positively correlated. In fact, it is not even important if these resources are shared among different vehicles; they could also be shared among different package options for the same vehicle.

Within the scope of this study, this means that sharing of operations allows the manufacturing firm to hedge against demand fluctuations. It is important to note that this effect is not captured in a deterministic analysis, potentially leading to an undervaluing of the strategic merits of operations sharing.

2.5 Material Transitions

In the previous chapter, the idea of resource sharing was introduced. It was applied to describe the relationship between products that are simultaneously produced on parallel
production lines. ‘Sharing’ means in that case that both products use, to a certain degree, the same resources, such as joining stations, equipment, tooling etc. If manufacturing resources are shared, production capacities of both products are overlapping.

However, vehicles are also frequently redesigned. Accordingly, the concept of sharing may also be used to describe the relationship between these different vehicle versions that are successively produced with the same resources. In this context, ‘sharing’ means that a certain fraction of the manufacturing resources used to manufacture the vehicle before the redesign can also be used in the production process after the redesign.

Figure 7 illustrates these two different dimensions to describe the relationships between vehicles. Vehicle A and B, simultaneously produced on parallel production lines, might share manufacturing resources (intratemporal sharing). After vehicle A has been redesigned to A’, a certain fraction of the manufacturing infrastructure needs to be replaced, but there are also resources that can still be used (intertemporal sharing).

![Diagram](image)

Figure 7. Different types of relationships between vehicles.

Notes: Two assembly lines fabricating two different vehicles (A and B) might share resources (intratemporal sharing). Two vehicles which are successively produced on a production line (A and A’) might also share resources (intertemporal sharing).

The concepts of intra- and intertemporal sharing are related to the idea of similarity between vehicles. Similarity describes how similar engineering requirements are, e.g. in terms of joining methods. Similarity between vehicles is a necessary condition for ‘sharing’ resources. In terms of material transitions, the similarity of designs determines the possible degree of intertemporal sharing. Similarity is a function of the versatility of joining technologies (see chapter 2.5.2).
2.5.1 Lightweight Materials

2.5.1.1 Overview

The automotive industry has reached highly advanced stages of development in terms of the performance of their material technologies. Current conventional production technologies "satisfy the conflicting demands of price, safety, performance, reliability, emissions, and market appeal" (Campbell, 2012: 660). However, after years of incremental improvements, the transition to lightweight materials means that carmakers have to address new technical problems, with a deadline for achieving improved performance set by regulation. In this sense, material transitions are not only capital-intense but they also force the carmaker to replace established (joining) technologies with innovative, but potentially error-prone alternatives.

The three main materials groups that have been regarded as promising alternatives to steel are high-strength ferrous alloys, light metals (aluminum, magnesium), and composites (Campbell, 2012: 662-663). Table 1 gives a comprehensive overview of those materials and presents the merits and challenges of each alternative. No matter which material is used, there will be challenges to overcome.

High strength steel, for example, is very similar to steel in terms of the thermal properties, so that existing manufacturing infrastructure can be used, but the opportunities to reduce weight are limited. Magnesium has a higher strength-to-weight ratio but is considerably more expensive. Another challenge is its limited machinability. Reinforced polymer composites may offer the highest benefits in terms of weight reduction, but longer cycle times lead to high cost. Aluminum could be the sweet spot between a general familiarity of manufacturers with metal forming and a still relatively high potential for weight reductions. As aluminum is notably softer and easier to damage during processing than steel, the assembly process includes more inspections and destructive testing. This may increase cycle times and requires expensive testing equipment. So far it is not clear which material will replace steel as the primary material in the automotive industry.
### Table 1. Summary of alternative lightweight automotive materials (Bandivadekar et al., 2008: 49).

<table>
<thead>
<tr>
<th>Material</th>
<th>Current Use</th>
<th>Merits</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>130 kg/vehicle, 80% are cast parts e.g. engine block, wheels</td>
<td>- Can be recycled</td>
<td>- High cost of Al</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Manufacturers familiar with metal forming</td>
<td>- Stamped sheet is harder to form than steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Softer and more vulnerable to scratches</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Harder to spot weld, uses more labor-intensive adhesive bonding</td>
</tr>
<tr>
<td>High-strength steel</td>
<td>180 kg/vehicle, in structural components e.g. pillars, rails, rail reinforcements</td>
<td>Makes use of existing vehicle manufacturing infrastructure; there is OEM support for near-term use</td>
<td>- More expensive at higher volume scale</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Lower strength-to-weight ratio compared to other lightweight materials</td>
</tr>
<tr>
<td>Magnesium</td>
<td>3.5 kg/vehicle, mostly thin-walled cast parts e.g. instrument panels and cross car beams, knee bolsters, seat frames, intake manifolds, valve covers</td>
<td>Low density, offering good strength-to-weight ratio</td>
<td>- Higher cost of magnesium components</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Production of magnesium in sheet and extruded forms</td>
</tr>
<tr>
<td>Glass-fiber reinforced polymer composite</td>
<td>Some rear hatches, roofs, door inner structures, door surrounds and brackets for the instrument panel</td>
<td>Ability to consolidate parts and functions, so less assembly is required - Corrosion resistance - Good damping and NVH control</td>
<td>- Long production cycle time, more expensive at higher volume scale - Cannot be recycled</td>
</tr>
<tr>
<td>Carbon-fiber reinforced polymer composite</td>
<td>Some drive shafts, bumpers, roof, beams and internal structures</td>
<td>Highest strength-to-weight ratio, offering significant weight-saving benefit</td>
<td>- As with glass fiber composites - High cost of fibers ($17-22/kg)</td>
</tr>
</tbody>
</table>

Notes: High-strength steel is the option which shows the most similarity to conventional steel but the opportunities to reduce weight are limited. This study focuses on aluminum, the second most popular lightweight material for automotive application. Aluminum is a promising material since it can be welded and shows a good formability. The biggest challenge is that it is difficult to spot weld, so that manufacturers need to switch to more expensive joining technologies.

### 2.5.1.2 MMLV

This study focuses on the transition from steel to aluminum. Ford provided detailed data sets for two different designs of the Ford Fusion – a conventional steel design as it is produced today and an aluminum-intense multi-material lightweight vehicle design (MMLV). These design-specific data sets are complemented by site-specific data, such as the station count, collected during site visits.
It should be noted that a transition from steel to aluminum is smoother than a transition towards composites due to aluminum's good machinability and weldability. All general arguments presented in this study are also true for other kinds of material transitions but transition cost and strategies might deviate.

2.5.2 Joining Technologies

A question that might be asked is what differentiates material transitions from ordinary product roll-outs using the same material. In order to understand this difference, it is essential to realize how joining methods make use of material properties. Nearly all methods used to connect two elements include the application of (a) heat, (b) pressure, (c) a secondary material, or some combination. The components' materials determine which of the different joining technologies are applicable. A wide range of methods has been developed: resistance spot welding, resistance seam welding, arc welding, friction welding, electromagnetic welding, roll bonding, diffusion bonding, arc brazing, laser brazing, self-pierce riveting, flow drill screws, blind riveting (Sakayama et al., 2013). Some joining technologies are more versatile than others, but all are suited to only a small range of base materials. Different process variants show differing degrees of compatibility with aluminum components.

The discussion in this paragraph is based on information provided by Omar (2011) in the book *The Automotive Body Manufacturing Systems and Processes*. Although the fusion welding process is an example of a quite versatile joining method, it still interacts with many different material properties. Two metallic elements are connected by creating a combined melting pool. Omar (2011) lists different process variants which use different heat sources such as an electric arc or a laser beam. The technique requires that both materials have a similar melting behavior and that local temperature spikes do not affect the material performance, e.g. as a consequence of grain growth. The most common variant used in the automotive industry is Mixed Inert Gas (MIG), an arc welding variant using inert gas to protect the melting pool from atmospheric contamination. According to Omar (2011), the configuration depends on many different material properties: (a) the combination of electrode and inert gas is selected based on the material's affinity to oxidize; (b) the power source and welding wire are chosen according to the material's thermal properties such as heat capacity and conductivity; (c) electrode diameter, wire feed, and weld travel speed are a function of
the base material. Hence, MIG welding can be applied to both steel and aluminum, but switching from one to the other requires replacing the power source, the electrode, the inert gas, and the welding wire, and to adjust all configuration parameters. Further investments in auxiliary infrastructure may also be required. Even when this joining method is applicable to aluminum and steel, the simple roll-out of a new steel design would require fewer adjustments than a material transition.

A related method widely used to join metal sheets is resistance spot welding (RSW). This is the primary method for automotive body assembly. An average BIW includes up to 5000 of these welds (Davies, 2012: 244). A current introduced between two electrode tips runs through both elements and creates a combined melting pool (Omar, 2011: 117). The materials' lead resistance, described by Ohm's law, is used to create a local heat spike at the contact point between both sheets (Omar, 2011: 118). In contrast to MIG welding, it is considerably more difficult to make resistance spot welding applicable to aluminum:

- The current required for spot welding aluminum is much higher due to its high thermal and electrical conductivity (Tab. 2). This means high power welding guns are required and conventional welding guns would have to be replaced (Ambroziak & Korzeniowski, 2010).
- A higher current can result in a shorter electrode life.
- Aluminum's tendency to form an oxide film, Al₂O₃, on the surface makes it necessary to mechanically or chemically polish the material before welding (Ambroziak & Korzeniowski, 2010).
- Due to the narrow range between softening and melting and aluminum's high thermal expansion coefficient, the control of tip force and current is very critical, leading to more failures (Davies, 2012: 252).

Since aluminum is hard to spot weld, often more labor intensive joining methods like adhesive bonding are used (Cheah, 2010). Even in cases when resistance spot welding is used, special equipment is required since the conventional equipment designed for steel welding is not able to provide the welding current needed for aluminum. In terms of carry-over of equipment after a material transition, aluminum spot welding is essentially a different technology than steel spot welding and requires new capital investment.
These examples illustrate that the base material determines the range of possible joining methods. A change of the material requires, in most cases, a change of joining methods and replacement of joining equipment. In the case of the body-shop area of automotive assembly plants, most of the capital costs are dedicated to joining methods and materials. The consequence is that it is very expensive to change the base material in an existing assembly plant and transition costs become critical. In contrast, a roll-out of a new design made of the same material does not require a switch of joining technologies to the same extent and is less capital-intense.

The ability of a manufacturing system to efficiently and quickly adapt to new material properties can be analyzed within the framework of product flexibility.

Table 2. Physical properties of steel and aluminum (Ambroziak & Korzeniowski, 2010; Oates, 1996).

<table>
<thead>
<tr>
<th></th>
<th>Melting temperature [°C]</th>
<th>Electrical Conductivity $10^4$ [S·m]</th>
<th>Thermal conductivity $10^4$ [W/cm·K]</th>
<th>Coefficient expansion $10^{-6}$·[1/K]</th>
<th>Density [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>1560</td>
<td>5–10</td>
<td>0.32–0.66</td>
<td>11.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>480–660</td>
<td>14.3–37.7</td>
<td>1.2–2.37</td>
<td>22–23</td>
<td>1.7–3.0</td>
</tr>
</tbody>
</table>

Notes: Joining technologies utilize material properties which differ for aluminum and steel. If steel is replaced with aluminum also the joining methods need to be changed or adjusted. In many cases, the joining equipment needs to be replaced.

2.6 Material Transitions and Product Flexibility

Car manufacturers operate in a highly dynamic market marked by increasing competition, steady technological developments, and a customer base that asks for more and more product variety and customization. In 2007, 400 different models were available on the marketplace in the US, in contrast to only 300 in the 1990s (Taub, Krajewski, Luo, & Owens, 2007). One result of this expanding product variety is that the average design life has become shorter and redesigns more frequent. It is true that, in most cases, these “body facelifts” are more a marketing instrument than a real product change and that the adjustments to the assembly

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7 “Design life” means here the time a certain design is being produced before it will be redesigned or replaced rather than the life-time of the product after it is sold.
line are limited. However, the ability to adjust the product according to macroeconomic shifts or changes of customers’ preferences has proven to be an important competitive advantage.

The ability “to changeover to produce a new (set of) product(s) very economically and quickly” has been studied as product flexibility (Browne et al., 1984). Koste and Malhotra (2000) applied the concept to the automotive industry and called it “new product flexibility”. They define it as “the heterogeneity (variety) of new products which are introduced into production without incurring high transition penalties or large changes in performance outcome”. Since this framing should include the case of a new product made of a new material, product flexibility seems to be the critical manufacturing capability that determines the penalties for the changeover to a new base material (see chapter 5.1). Accordingly, the costs of the changeover to a new material can be regarded as flexibility penalties.

As discussed in the previous chapter, these transition costs depend on the compatibility of manufacturing system and materials. This dependency shows that the degree of product flexibility of a manufacturing system also depends on both the system’s current state (and capabilities) and the state it is going to (and its capabilities in that state). Many researchers have tried to quantify different types of manufacturing flexibilities and attempted to better understand the trade-offs between them (Gupta & Goyal, 1992; He et al., 2011; L. L. Koste & Malhotra, 2000). The bitemporal modeling framework applied in this study (Fig. 3) might be a valuable tool to assess the system’s sensitivity to change as a metric for the intrinsic level of product flexibility.

A better understanding of product flexibility could be beneficial because it helps to answer the question how flexible a manufacturing system should be designed, now, to “accommodate product changes in the future” (Persentilli & Alptekin, 2000). A decision-maker who anticipates a shift to a lightweight material could consider future engineering requirements when dimensioning new plant facilities. During the last decades, this trade-off between current cost and future benefits has mainly been studied for the field of capacity planning (for a review see A. De Toni & Tonchia, 1998). These studies were conducted when the versatility of new products was limited to the general design – and not the material. However, the review of BMW’s and VW’s material strategies in chapter 2.2 shows that the automotive industry is heavily divided regarding future materials trends. This means there is a high level of uncertainty regarding future manufacturing requirements. It might be
beneficial to be prepared for the changeover to one or more lightweight materials. In this sense, materials flexibility can be studied as a sub-element of product flexibility.

2.7 Activity-Based Costing

Johnson and Kirchain (2009) present cost modeling as an approach “built around the fundamental concept that costs derive from the use of resources” (Johnson & Kirchain, 2009). Their proposed framework, frequently applied by MIT’s Materials Systems Laboratory (Field et al., 2007; Kirchain & Field, 2001), treats vehicles as a collection of independent subassemblies. These subassemblies correspond in most cases but not necessarily to functional groups of components in the real vehicle, such as the front structure or the bodysides. This simplification reduces the burden of data sourcing and makes the approach applicable on earlier stages in the design process where design data for single parts is often missing. However, it is important to point out that these ‘subassemblies’ do not reflect a collection of parts but rather a set of physical activities. More precisely, they are accounting instruments that capture all joining operations performed on parts included in the specific subassembly and reflect the engineering effort from which the resource requirements are projected. These sets of activities provide the basis to proportionally allocate total fixed cost to single subassemblies or models. This accounting strategy is called activity-based costing (Park & Simpson, 2008). Park and Simpson (2008) explain that the approach differs “from traditional costing systems by modeling the usage of all resources on the activities performed by these resources and then linking the cost of these activities to products”.

It becomes obvious how critical manufacturing activities are in the cost assessment. They determine the total resource requirements, as well as their allocation to cost objects. As presented in chapter 2.5, the quantity and extent of assembly activities is mainly a function of joining methods and materials. An interesting question is what happens if these activities, on which the entire cost estimation is based, are transformed due to changing engineering requirements. Materials transitions are the source of such a change of engineering requirements. They have a distinct impact on the foundations of conventional cost assessment.

The model developed for this study is a macroscopic accounting-based approach to material transition cost. First, the model calculates the cost in both the initial and the final
state based on activities and then it applies a macroscopic accounting framework to assess the cost for the transition between these states. Further research could shed light on the microscopic implications of material transitions by modeling the microscopic changes of activities and then aggregate these effects up to the total transition cost. This bottom-up approach would be in line with the idea of engineering-based cost modeling (Field et al., 2007) and might help to better understand the microscopic nature of material transitions.
Chapter 3 – Transition Cost Modeling

The transition cost model is a combination of a process-based cost model (chapter 3.1) and a transition cost module (chapter 3.2). The details of the process-based cost model are not discussed at this place (for a discussion see Field et al., 2007; Johnson & Kirchain, 2009; Kirchain & Field, 2001). The transition cost module takes data sets from the process-based cost model and generates a range of economic benchmarks (chapter 3.3), which are used to analyze different transition scenarios. These calculations simplify the complex manufacturing environment and the scope is certainly limited. Once the structure of the model is laid down, it can be used to analyze specific cases (chapter 4).

3.1 Process-Based Cost Model Output

The process-based cost model takes information about design-specific engineering requirements (e.g. number of connects for each subassembly), plant-specific operation parameters (e.g. working days per year), and parameters describing the manufacturing strategy (e.g. which subassemblies are shared) to calculate resource requirements (e.g. number of joining stations). They are used as a basis to estimate total capital costs for tooling, joining stations, and different types of equipment (positioning, transportation, loading, dispensing, material supply) for each subassembly independently. Capital costs are not only cost-effective but also reflect the infrastructure’s value after the start of production. For each changeover, they are sequentially calculated for the initial and final state and loaded with engineering requirements and design parameters into the transition cost module (Fig. 3). These data sets provide the basis for all further cost assessments. As the initial and final state of a changeover correspond to different points in time, this thesis refers to this approach as bitemporal transition cost modeling.

3.2 Transition Cost Module

3.2.1 Overview

The transition cost module is essentially a complex accounting tool. Based on a numerical representation of engineering requirements in the initial and final state, the model calculates investment flows going into the system and out of the system. These investment flows are
taken as a basis to compute the additional investment that is required to adjust the manufacturing capabilities to the new engineering requirements after the changeover to a new material. The boundary conditions of the transition have to be set by the user.

For this study, the transition cost module is set up to compute investment flows for transition scenarios with a maximum of three time periods and two vehicles per plant. This means one material transition scenario can consist of a maximum of two single changeovers— one for each vehicle in the plant.

3.2.2 Investment Components

In order to construct the investment flows and recognize the differences between them, it is important to have a good understanding of the different investment components. These investment components result from the different types of resource sharing (intratemporal and intertemporal sharing, introduced in chapter 2.3). Figure 8 depicts the entirety of resources used in the production process of a vehicle as the surface area of a cycle. Resource sharing is illustrated as overlapping areas. Areas 2 and 3 correspond to intertemporal sharing and areas 4 and 5 to intratemporal sharing.

Each of the following paragraphs discusses one of the areas shown in Fig. 8.

![Figure 8. Overview of different investment components for a material transition.](image)

Notes: The area of a cycle represents the entirety of resources used in the production process for this vehicle. The underlying transition scenario is the same as for Fig. 7. In the initial state, the plant produces vehicle A and B. Vehicle A is replace by vehicle A'.
3.2.2.1 Area No.1

The graphic shows that some of the resources used for vehicle A are useless after the transition. These machines, tools, joining robots etc. might go for scrap or if they have salvage value generate return. The market value, for which these assets can be sold, is a function of both remaining lifetime and value when new. Since the market value is in most cases smaller than the net present value of outstanding liabilities incurred to finance the assets, a company that sells them before the end of life typically incurs a financial loss. The magnitude of this financial loss is a function of the assets remaining lifetime. This shows that timing of material transitions is an important strategic decision. The difference between market value and net present value of respective outstanding liabilities is a major source of the path dependency which was discussed in chapter 1.

3.2.2.2 Area No.2

Resources that were solely used for vehicle A and can now be reused for vehicle A' are most favorable. Assuming that the output rate is the same for vehicle A and A', a machine's capacity laid out for the output rate of vehicle A has the same utilization rate when used for components of vehicle A'. This carry-over of capital is beneficial, as it reduces the capital requirements, compared to the case when the complete equipment would need to be replaced. The question is how this carry-over can be maximized. Either the system is versatile and adjustable to new materials or the new vehicle design, A', is designed in a way to match existing manufacturing capabilities. This investment component is the working point of product flexibility.

3.2.2.3 Area No.3

Initially shared resources that are also shared in the final state have similar implications as those illustrated in area 2. However, there are important differences. A machine that is expected to process two different components for two different vehicles needs twice the capacity of an unshared machine. It is a reasonable assumption that this shared machine (e.g. a joining station) needs at least to be reprogrammed or adjusted once the changeover of one of the vehicles is initiated. To do this, the machine is stopped or turned down. This has side

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8 This is the case if the market value follows a straight line depreciation and the liability bears interest.
effects on the output rate of the second components (for the unchanged vehicle) produced on
the machine. These effects aggregate to a reduced output rate of vehicle B during the
changeover of vehicle A.

3.2.2.4 Area No.4

Resources were initially shared between vehicle A and B but are useless for vehicle A'. The
machines were laid out for the combined production volume of vehicle A and B. After the
production stop of vehicle A, they have twice the capacity required for vehicle B alone. The
capacity can be split if the combined production volume of A and B was realized e.g. with
two machines. The capacity cannot be split if it was reached with one large machine instead.
Obviously, the reality lies somewhere between both extremes. The fraction of the combined
production capital that cannot be split is sunk as it cannot be exploited for the production of
vehicle B, is useless for vehicle A', and cannot be sold on the market. This overcapacity
should be minimized. In this example, product (material) flexibility would be higher for two
small machines than for one large machine.

3.2.2.5 Area No.5

This area mainly represents two different cases.

New machines need to be purchased for the production of vehicle A'. These machines
might be more versatile or advanced than (older) machines, which were required for the
production of vehicle B, and can handle both different component types, for vehicle A and B.
In this case, some other unshared machines used in the production of vehicle B become
useless after the changeover of vehicle A (not shown in the graphic).

In the other case, initially unshared resources, used only for vehicle B, can also be
utilized for components of vehicle A'. The downside could be that machines need to be
adjusted or reprogrammed. This might again have a disturbing effect on the output rate of
vehicle B.

3.2.3 Investment Flows

Each of the different investment components, which are discussed in chapter 3.2.2, is either
source or sink of an investment stream between the initial and final state of a material
transition. As a result of structural differences between investment components, different investment streams have to be modeled differently and careful accounting is essential.

Figure 9 expands the scope of Fig. 8 by adding investment streams and investment volume. The underlying transition scenario is the same as for Fig. 8 and Fig. 7. The footprint of a “vehicle box” illustrates the variance of equipment (similar to the surface area in Fig. 8) and the height at each point conceptually corresponds to the capacity of this specific type of equipment.

![Figure 9. Overview of investment flows for a material transition.](image)

Notes: The footprint of a “vehicle box” illustrates different types of equipment (variance of equipment) used in the production process. The height represents the capacity of this type of equipment. The volume corresponds to the total capacity required. Overlapping surface area (shadow) illustrates intertemporal sharing and intersecting volume corresponds to intratemporal sharing.

The goal is it to estimate the difference between investment streams going into the system and out of the system in Fig. 9. This difference,

\[ I_{\text{trans}} = (I_a^{\text{unshared}} + I_a^{\text{shared}}) - (D^{\text{shared}} + D^{\text{unshared}}) \]  

with additional investment, \( I_a \), spent for shared and unshared resources and disposal value, \( D \), of shared and unshared resources, equals the investment cost of the transition. Both
components, the additional investment needed and the total disposal value, are functions of the different resource streams going from the initial state to the final state (see internal arrows in Fig. 9). They are modeled differently dependent on their characteristics in terms of resource sharing. All following terms only concern resources used for the vehicle that undergoes the transition, A, while the second production line, B, in the plant is assumed to be unaffected.

\[ \text{I}_{a,\text{shared}} \propto \sum_{i,j,z} \left[ V_{i,j,z}^{\text{shared,final}} - (\alpha_{i,j,z}) \cdot V_{i,j,z}^{\text{shared,initial}} - (1 - \alpha_{i,j,z}) \cdot V_{i,j,z}^{\text{unshared,final}} + \eta_{i,j}^{\text{shared}} \cdot (\alpha_{i,j,z}) \cdot V_{i,j,z}^{\text{shared,initial}} \right] \]  

(2)

\[ \text{I}_{a,\text{unshared}} \propto \sum_{i,j,z} \left[ V_{i,j,z}^{\text{unshared,final}} - (1 - \alpha_{i,j,z}) \cdot V_{i,j,z}^{\text{unshared,initial}} - \eta_{i,j}^{\text{unshared}} \cdot (\alpha_{i,j,z}) \cdot V_{i,j,z}^{\text{shared,initial}} \right] \]  

(3)

\[ D_{\text{shared}} \propto \sum_{i,j,z} \left[ \frac{(\text{restlife})_{i,j}}{(\text{lifetime})_{i,j}} \cdot \eta_{i,j}^{\text{disp}} \cdot (1 - \alpha_{i,j,z}) \cdot V_{i,j,z}^{\text{shared,initial}} \right] \]  

(4)

\[ D_{\text{unshared}} \propto \sum_{i,j,z} \left[ \frac{(\text{restlife})_{i,j}}{(\text{lifetime})_{i,j}} \cdot (1 - \alpha_{i,j,z}) \cdot V_{i,j,z}^{\text{unshared,initial}} \right] \]  

(5)

\( i = \text{subassembly (e.g. front structure, bodysides)} \)

\( j = \text{type of equipment (e.g. transportation, loading)} \)

\( z = \text{type of cost (e.g. non-reusable, reusable)} \)

\( \alpha_{i,j,z} = \text{relative carry-over of investment between A and A' (between 0% and 100%)} \)

\( \eta_{i,j}^{\text{shared}} = \text{parameter that describes the fraction of the shared resource that can be split off to be used for the new vehicle (between 0% and 100%)} \)

\( \eta_{i,j}^{\text{disp}} = \text{parameter that describes the fraction of shared resource that can be split off to be disposed (see chapter 3.2.2.4; between 0% and 100%)} \)

\( \left( \frac{\text{restlife}}{\text{lifetime}} \right)_{i,j} = \text{depletion ratio} \)

\( V_{i,j,z}^{\text{shared-unshared,initial}} = \text{value of resource in initial state that changes from being shared to being unshared} \)

\( V_{i,j,z}^{\text{shared,final}} = \text{value of shared resource in final state} \)

\( V_{i,j,z}^{\text{shared,initial}} = \text{value of shared resource in initial state} \)

Figure 9 also illustrates the shift of shared capacities in the course of material transitions. Vehicle A' requires partly different resources than A (the footprint is orientated differently). This means that there might also be other opportunities for resource sharing (the intersecting
volume is located differently). The different ways existing resources can eventually be shared and utilized for new vehicles is a manifestation of product flexibility.

It would be possible to expand the scope to more than two vehicles in the plant, but resource sharing among the production of three vehicles would significantly increase the complexity of the accounting procedure.

3.2.4 Outputs

The model computes the volume of each of the investment streams depicted in Fig. 9. Using Eq. (1), total investment cost of the full material transition can be estimated.

Excluding information about the vehicle designs, a transition scenario is specified by around 257 parameters. The model can be used to assess the impact of each of these single parameters on transition cost. However, many of the arguments that have been presented revolve around the idea of inter- and intratemporal resource sharing. Resource sharing is not an input to the transition cost model but rather an intermediate result. The degree of resource sharing is calculated on the way between input data and transition cost.

In the case of intratemporal sharing, the manufacturing strategy is an input to the process-based cost model. This input also indicates which subassemblies of different vehicles are assembled by the same joining stations. All resources dedicated to these stations are in this case regarded as shared. The ratio in the initial and final state between investment cost of shared resources and the sum of all resources needed is interpreted as the relative degree of intratemporal sharing. This ratio between 0% and 100% is calculated by the transition cost module and based on investment data provided by the process-based cost model.

The degree of intertemporal sharing is quantified by relating the investment requirements in the final state to the carry-over of investment from the previous manufacturing state. The carry-over corresponds to the subtracted terms in Eqs. (2) and (3) and is generated by the transition cost module. The ratio between investment carry-over and investment requirements varies between 0% and 100% and is taken as a metric for intertemporal sharing.

Both ratios are rather a simplistic metric for resource sharing, but they help to investigate the relationship between sharing strategies and transition cost.
3.2.5 Generic Case

The purpose of this chapter is to introduce the general structure of further case studies. As previously mentioned, the model is set up to handle maximum two vehicles in the plant at the same time. This results in maximum three transition states – an initial state, an intermediate state, and a final state (Fig. 10). The initial state is characterized by the production of two conventional steel vehicles on two different production lines. Dependent on the case study, both production lines in the plant can share resources (intratemporal sharing). The intermediate state features a mixed-material production when one production line was already switched to the production of an aluminum intense multi-material vehicle (MMLV) and the second production line still processes steel vehicles. Each changeover is characterized by a carry-over of resources (intertemporal sharing). Once the second production line has been switched to the production of MMLV-type vehicles, the material transition is completed.

The transition scenario can be described by a set of three intratemporal sharing ratios and two intertemporal sharing ratios (3+2=5). It should be noted that the same transition scenario always results in the same set of sharing ratios. However, the same set of sharing ratios can theoretically be realized with an infinite number of different transition scenarios. This means that sharing ratios can certainly help to identify cases, but an assessment of cost effects purely based on them might be misleading.

![Figure 10. Structure of further case studies.](image-url)
3.3 Unit Cost

Figure 11 presents all cash flows occurring in an example transition scenario. Note that the timing of both changeovers is adjustable in the transition cost model. To ease the reader's understanding of this example, the transitions have been fixed to periods five and eight (see Appendix A for a general form; Fig. 11 and Eq. (8) represent this fixed example). The plot shows initial investment cost (Fig. 11-1), transition cost (Fig. 11-3, 5), and variable production cost in the initial (Fig. 11-2), intermediate (Fig. 11-4), and final state (Fig. 11-6). It is assumed that for every investment a loan is raised having a duration equal to the asset’s lifetime. By doing the account this way these future liabilities are independent of the actual asset, so that the asset can be sold at any point in time. In periods five and eight, when additional capital is invested, the long-term liabilities of earlier investments are ongoing and still have to be redeemed with annual payments. The light blue bars labelled with (7) and (8) in Fig. 11 illustrate all future liabilities in these both periods. In the same periods, new capital is required, which is again provided by loans. As long-term liabilities accumulate over the course of the transition, the total annuity payment also increases (see Appendix B for details). Furthermore, the transition of a production line always means that some fraction of the equipment and tools becomes useless. The framed bars illustrate the salvage value of assets which are sold on the market (Fig. 11-7, 8).

In order to analyze the cost effect of material transitions and the path dependency of unit costs, the analysis in this study applies per vehicle accounting. However, allocating fixed costs and transition costs to units of production is non-trivial. Each accounting method is based on certain assumptions which all affect the meaning of the later cost result. In the following, two different approaches are presented, including a brief discussion of their characteristics.
Figure 11. Overview of payments during a transition scenario.

Notes: (1) Initial investment for tools and equipment; (2) cumulative variable production cost per year for initial plant setup; (3) intermediate net transition cost for tools and equipment; (4) cumulative variable production cost per year for intermediate plant setup; (5) final net transition cost for tools and equipment; (6) cumulative variable production cost per year for final plant setup; (7), (8) carry-over of liabilities from previous periods, salvage value of sold equipment and tools.

3.3.1 Static Unit Cost

As discussed above, the conventional approach to calculate unit costs is based on the assumption that investment costs are paid off over the assets’ lifetime. When all liabilities are redeemed, the asset is assumed to be fully ‘depleted’ and has lost all of its value. Thus, the fixed cost component of unit costs can be calculated by spreading investment costs over all units produced before the end of life. These annuitized investments are summed up with variable yearly production costs and related to the yearly production rate. This gives

\[ C_{\text{steel}} = AN(I_{\text{steel,initial}}^t, t_{\text{eff}}, r) + c_{\text{steel, var}} \times (Y_{\text{steel}})^{-1} \]  
(6)

\[ C_{\text{mm lv}} = AN(I_{\text{mm lv, initial}}^t, t_{\text{eff}}, r) + c_{\text{mm lv, var}} \times (Y_{\text{mm lv}})^{-1} \]  
(7)
with fixed yearly production volume, $Y$, initial investment, $I_1^{\text{initial}}$, and constant total variable cost per year, $c^\text{par}$, for the steel and MMLV version, respectively. The annuity, $AN$, is calculated based on the effective average lifetime of capital assets $t_{\text{eff}}$, and discount rate, $r$.

This static calculation corresponds to a greenfield approach (i.e., building a new plant dedicated to a specific production schedule and with zero value for producing any other product) and computes the investment theoretically required to set up a new production facility. Capital assets which might already be in place and outstanding liabilities are ignored.

### 3.3.2 Partial Transition Unit Cost

In the case of a transition to a new vehicle type, existing capital assets and liabilities can still be cost-effective in production and their value needs to be included when accounting unit production costs.

In order to make a fair comparison among different transition strategies on MMLV unit cost, the cost effects of the transition should only affect costs after the transition was initiated, leaving unit cost in previous years unaffected (for details see Appendix B). Post-transition unit costs are calculated as

$$C_{\text{trans}} = AN \left[ \left( a_{5-10}^{5-10} \cdot I_{\text{steel, initial}} + \beta_{5-10} \cdot \frac{I_{\text{trans}}}{(1+r)^i} + \gamma_{8-10} \cdot \frac{I_{\text{trans}}}{(1+r)^i} + \sum_{i=5}^{10} \frac{c^\text{par}}{(1+r)^i} \right), 6, r \right] \cdot \left[ \frac{10 Y_i}{6} \right]^{-1} \tag{8}$$

with year, $i$, combined production output per year, $Y_i$, initial investment, $I_{\text{steel, initial}}$, capital costs of the first transition, $I_{\text{trans}}$ (index corresponds to the numbering in Fig. 11), capital cost of the second transition, $I_{\text{trans}}$, and total variable production cost per year, $c^\text{par}$. Operators $\beta_{5-10}$ and $\gamma_{8-10}$ adjust the transition cost, $I_{\text{trans}}$ and $I_{\text{trans}}$, to the fraction that is paid off over the last five and last two years of the ten-year scenario, respectively. Thus, the term

$$\beta_{5-10} \cdot \frac{I_{\text{trans}}}{(1+r)^i} + \gamma_{8-10} \cdot \frac{I_{\text{trans}}}{(1+r)^i}$$

\tag{9}

gives the net present value in period four of all liabilities generated by both changeovers and redeemed between year five and year ten. The operator $a_{5-10}^{5-10}$ has the same function for the

---

9 The effective, average lifetime is rather an artificial concept. The total investment is composed of assets, $i$, with varying lifetimes, $t_i$. The effective, average lifetime is given by $AN(\sum_i l_i, t_{\text{eff}}, r) = \sum_i AN(l_i, t_i, r)$. 

49
initial investment. It adjusts the initial investment to the fraction that is paid off between year five and year ten and discounts these partial investment cost to period four. The resulting expression

\[
\left( a_{5-10}^{0-4} \cdot i_{1}^{\text{steel, initial}} + \beta_{5-10} \cdot i_{8}^{\text{trans}} + \gamma_{8-10} \cdot i_{8}^{\text{trans}} + \sum_{i=5,10} C_{\text{tar}}^{i} \right)
\]

(10)
gives the net present value in period four of all liabilities paid off between period five and ten. Based on this net present value, Eq. (8) calculates the annuity for the six periods and divides it by the average yearly production volume.

This approach is still a great simplification since the production volume of steel vehicles in the intermediate state (see Fig. 11-4) is lumped together with the MMLV production volume after year five. By doing this, some fraction of the cost premium for the lightweight vehicle is added to the unit costs of the intermediate steel vehicle. As results are only compared relatively to each other, this effect should be acceptable.
Chapter 4 – Case Studies

In the previous chapters, all relevant concepts and tools have been laid out, so that the model can now be applied to different scenarios. Results are compared with conventional cost figures to shed light on the strengths and weaknesses of the modeling approach presented in this study.

In the conventional cost assessment (Static Cost Assessment; Fig. 12), potential unit costs of the lightweight vehicle are compared with unit costs of the steel vehicle, assuming a greenfield approach for both production facilities. Equations (6) and (7) show how static unit costs are typically calculated. Based on the difference between them, a cost-benefit analysis is conducted and the decision is made whether or not a transition makes economic sense.

In contrast, the transition cost modeling approach (Transition Cost Modeling; Fig. 12) computes unit costs of the lightweight vehicle taking into account the path that needs to be taken to implement the new vehicle into the existing manufacturing system. In this study, transition unit costs are computed using Eq. (8). The usual refresh cycle provides the opportunity to either change to the production of MMLVs or to redesign the current steel vehicle. Therefore, the respective reference scenario is a refresh of the steel vehicle. This refresh scenario is counterpart to static steel unit costs in the static cost premium calculation (Eq. 6). The transition costs per vehicle that need to be paid for the introduction of the MMLV is calculated as the difference in unit costs between the “new steel vehicle”, after the refresh, and the MMLV.

Figure 12 illustrates both of these concepts side by side. Every transition scenario can be defined according to the degrees of intertemporal and intratemporal resource sharing between vehicles (see numbering in Fig. 12). If the scenario is slightly adjusted in order to analyze the cost effect of different strategic decisions, also the sharing ratios will change. Thus, they can be used to identify different scenarios and to analyze otherwise discrete scenario changes (e.g. component-wise) on a continuous scale. Sharing ratios are used as a general framework to structure the further analysis.

Three cases are presented, which address when (chapter 4.1), to what extent (chapter 4.2), and how (chapter 4.3) a material transition should or should not be realized.
4.1 Timing of Material Transitions

The transition cost modeling approach differs from the static cost assessment in that the base case, against which the production costs of a lightweight MMLV vehicle are compared, is also a dynamic reference scenario rather than a static reference state. This reference state takes into account the fact that, even without considering a material transition, an automaker’s manufacturing infrastructure experiences frequent adjustments in the course of routine product or process changes. Some time periods may be more or less capital-intensive, dependent on the extent of modifications required. In order to correctly account for the cost differences that a materials transition might entail, the cost analysis must consider a parallel set of manufacturing transitions that do not include a material transition. Moreover, this extended time-line for analysis introduces the opportunity for a wider set of strategic choices, which must also be reflected in the analysis. The decision-maker has actually the opportunity to decide between both scenarios at every possible transition point.

The importance of the reference scenario for assessing a transition strategy can be illustrated with a simple example: At the beginning of the new year, a car owner is offered a
scrapping incentive, $B$, for his old car if he replaces it with a new version of the same type within the next 12 months. The new version has exactly the same features, but requires no repair work in contrast with his old car. The sales price is $P$. The car owner's net costs of the new car are $C = P - B$. Thus, for the net investment $C$ he can replace his old car at any point in time within 12 months. Assume that $C$ is exactly the amount he has in his interest-paying bank account at the beginning of the year. Now, assuming he has perfect information about future repair costs of his current car, a cost minimizing actor will buy the new car at the point in time when two conditions are true: (a) the net present value of all future repair costs at the respective point in time are higher than $C$; (b) the amount in his bank account (including expenses for repair work) is at its maximum. This simple example already has a non-trivial optimal transition point, which heavily depends on the economics of the reference state.

This case study is an attempt to understand how the optimal transition point reacts to changes in the reference scenario.

### 4.1.1 Overview

In the material transition context, $P$ can be regarded as total transition costs and $B$ as additional economic benefits of the lightweight vehicle. The net cost of this transition, $P - B$, has to be compared with a manufacturing development plan that does not include a new material vehicle, so both the cost $P$ and the benefit $B$ of the lightweight alternative have to be compared with a $P$ and $B$ associated with a more incremental design strategy. The following case explores which conditions in the reference scenario would promote a material transition.

In this analysis, the advanced materials transition scenario is kept constant and compared with two different steel material reference states – a simple facelift and a general structural redesign. The equivalent in the abovementioned car owner example would be that the net investment required to buy the new car, $C$, is kept constant and the repair requirements for the old car are varied. The facelift and redesign scenarios are computed by adjusting the degree of intertemporal sharing between the base steel vehicle in the initial period and the ‘new steel’ vehicle after the refresh (Fig. 13-2b). It is assumed that the degree of intertemporal sharing is the same for both changeovers. Across all scenarios, platform sharing (front structure, underbody) is assumed.
Notes: The degree of intertemporal sharing (2b) is used as a handle to switch between different refresh scenarios. Varying this sharing ratio allows for switching between a general structural redesign (sharing ratio low) and a simple facelift (sharing ratio high).

4.1.2 Structure

Table 3 shows the cash flows and output rates for all three scenarios, computed by the transition cost module. All further analyses are solely based on these cost figures. In order to calculate transition unit costs for the three scenarios, Eq. (8) is applied to the respective cash flows (see Appendix B).
### Table 3. Cash flows of first case study.

#### - Facelift -

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Diff. from Facelift* (T$) 69,802 57,452 49 40
Diff. from Redesign* (T$) 69,802 32,404 49 23

*Cash flows were discounted before taking the difference (r=6.1%)
4.1.3 Results

Results of this case study are summarized in Fig. 15. The following paragraphs will each discuss one feature of Fig. 15. The bar charts illustrate cash flows for the facelift, redesign, and transition scenario. The table in Fig. 15 presents a cost comparison between the material transition and both different steel scenarios.

4.1.3.1 Facelift

For a facelift, only the front structure is redesigned in period five and eight, without affecting other components of the steel vehicle. Therefore, the scenario is characterized by relatively low investment requirements in both transition periods (7,041,000$ and 7,481,000$, compare with Tab. 3). Also the salvage value of sold tools and equipment is comparatively small, reflecting the small changes entailed in facelift conversion.

The sum of ‘Net Tool&Equipment Investment’ and ‘Carry-Over Liabilities’ in respective bar chart in Fig. 15 conveys the net present value of all liabilities outstanding. These include not only liabilities incurred to finance assets which are still effective in the production, but also liabilities for those assets which have already been replaced in the course of the first facelift in period five. As additional capital requirements for the facelift are small, more liabilities can be paid off over time than new liabilities are incurred to finance them. The result is that the value of all future liabilities decreases from period five to period eight.

4.1.3.2 Redesign

The redesign scenario is based on the assumption that joining equipment for all components requires adjustments in periods five and eight. As a consequence, the additional investment in both transition periods is higher than in the facelift scenario periods (25,435,000$ and 25,734,000$; compare with Tab. 3) and also more manufacturing equipment is sold to the market, leading to a higher book value of replaced assets.

As ‘Carry-Over Liabilities’ in period five only depend on the initial investment and the number of pay-off periods, they are unaffected by the decision in period five. Thus, they are identical as in the previous scenario, but their corresponding book value will be much smaller after the first changeover, since a higher fraction is sold before the end of life. This effect is carried on to the next transition point in period eight. Because more additional capital was needed in period five, ‘Carry-Over Liabilities’ are now increased compared to the facelift
scenario. Again, more equipment is sold, so that the difference between outstanding liabilities and actual book value (including realized salvage value) increases. For all of these reasons, this scenario is more expensive than the simple facelift scenario.

4.1.3.3 Transition

In the material transition, joining equipment changes for all components requires capital-intense adjustments. The additional investment in period five is about 1.8x higher than in the redesign scenario (64,039,000$ and 31,665,000$; compare with Tab. 3), but the total salvage value of sold manufacturing equipment increases only slightly. The reason is that more dedicated equipment (e.g. tooling) is sold, which is assumed to have a smaller market value than non-dedicated equipment. In period eight, when again considerable capital is invested, the net present value of all future liabilities (the sum of ‘Net Tool&Equipment Investment’ and ‘Carry-Over Liabilities’) is notably higher than the initial investment in period 0. This shows that equipment change-out before capital costs are paid off leads to an accumulation of outstanding liabilities over time, particularly when capital needs are high and the total salvage value limited. The consequence is that a material transition results in a high capital loss on equipment that is sold off without recovering its full accounting value, which therefore adds a capital burden to the advanced material alternative.

4.1.3.4 Cost Comparison

Equation (8) was applied to the cash flows of each of the three scenarios (Tab. 3) to calculate transition unit costs. Results are presented in the table in Fig. 15. The calculation yields unit costs for the steel vehicles in the facelift and redesign scenario of 309$ and 335$, respectively. For the material transition scenario shown in Fig. 15, MMLV unit costs of 511$ were computed. Static unit costs for the steel vehicle, which are not a function of the transition scenario, are 276$.

4.1.4 Discussion

4.1.4.1 Alternative-Driven

If the benefits of moving to a lightweight vehicle could be captured in the market price of the new vehicle, then the economic merit of the transition to the firm (in this case win margin)
could be calculated as the difference between unit costs and sales price. Thereby, the
carmaker chooses between benefits of a steel and MMLV production.

In reality, the merits of a lightweight vehicle are rarely reflected in the market price. In
the absence of a fully valued market price, an analysis typically starts with a comparison
between unit costs, which can be developed without consideration of market pricing. The
difference in cost between the alternative and some base case or reference state is called the
cost premium of the alternative. Once calculated, this cost premium can be put in context
with a potential, but speculative, net benefit of the lightweight vehicle, grounded in both
economic and strategic measures (avoided environmental damage, reduced fuel costs,
avoided regulatory penalties, etc.).

The table in Fig. 15 presents the MMLV transition premiums, or in other words, the
additional costs of the MMLV, compared with the two different steel scenarios as a reference
cases. They are calculated as the difference in transition unit costs between the MMLV
scenario and each of the steel scenarios.

For a given MMLV transition scenario with transition unit costs of 511$, results show
that effective costs of a material transition are higher if a facelift is the alternative
(202$=511$-309$) than if a redesign would be required instead (176$/unit =511$-335$). The
higher the costs of the alternative scenario, the lower are the additional costs of the material
transition.

Note that the static greenfield cost comparison would always suggest that the
introduction of the MMLV entails a cost premium of 184$, failing to take into account the
different change penalties of the different steel reference scenarios. This example illustrates
that dependent on the timing, the effective unit transition cost premium varies between +10%
and -4%, compared to the static cost assessment. Depending on the estimated value of the
transition, this difference could have a significant effect upon the choice of action, and may
distinguish an economic from an uneconomic transition.

Another way to consider the implications of this result is to note that these values
suggest that the cost effective material choice is likely to depend upon the plans for a vehicle
platform development over the product lifetime. If, at a given transition point, only a simple
facelift is planned, Fig. 15 suggests that the carmaker could wait until a structural redesign is
planned before initiating a transition towards the MMLV design. In effect, the analysis
suggests that there are merits to waiting for better opportunity, in a strategic sense, to arise. This essentially assigns a value to an option to wait; a concept that has extensively been studied as real option theory (first mentioned by Myers, 1977; see also Dixit & Pindyck, 1994). Note that this option cannot be valued when using a static cost assessment, as both alternative states are assumed to stay unchanged over time.

4.1.4.1 Deterministic Optimization

If the assumption is dropped that material transitions necessarily follow a fixed refresh cycle and can instead be initiated at any point in time, the scope of the analysis needs to be extended. In this case, many different forces simultaneously push the optimal transition point in both directions on the timeline.

If the material transition can theoretically be conducted at any point in time (but has to be completed by the end of the ten-year period), costs and benefits do not compete with economics of a steel refresh. The costs of the reference state are not relevant for the decision anymore. In this case the optimal transition points for both production lines minimize overall production costs. Therefore, it is not sufficient to analyze only costs after the transition, as it is done with Eq. (8).

The attempt to minimize total production costs over the full ten-year period creates the problem that different vehicle types in initial, intermediate, and final state are lumped together is the same optimization. Both have different production costs, but also different benefits. If the analysis is grounded solely in the cost of production, every cost assessment would always come to the conclusion that it is better to switch as late as possible because of the effects of discounting, favoring the delay of major expenses into the future. Furthermore, if a higher fraction of the overall production volume corresponds to steel vehicles with lower variable production costs, total production costs would necessarily be reduced.

The transition cost model was applied to quantify this effect. Figure 14 presents results of an extended analysis, using the material transition scenario illustrated in Fig. 15 as a basis. The plot relates relative overall production costs versus the timing of the transition. As this figure shows the lowest cost transition scenario is also the one in which the transitions occur as far in the future as possible.
Notes: Relative total production costs for the ten-year period are shown as a function of transition periods. The case with changeovers in periods one and three is taken as a reference point.

Both previous approaches, the alternative-driven approach and the deterministic optimization, try to answer the question of optimal timing in a different context with a different set of assumptions. Decision rules which can be derived based on both approaches differ widely. It is essential to select the framework that fits best with the actual decision situation.

The alternative-driven approach analyses the problem according to a decision tree framework, where in every possible transition node the decision has to be made whether or not a material transition should be initiated. Here, decisions were shown to depend heavily on costs in the alternative scenario. The more costly the alternative branch of the decision tree is, the higher the motivation to switch the material. The option to wait has a value and could be analyzed with frameworks known from real option theory.

The deterministic optimization addresses the problem from a different angle and focuses on the overall NPV. The problem here is that the production of a lightweight vehicle is more expensive and a later transition always optimal if benefits are ignored. This strong effect covers most other cost relationships.
Figure 15. Alternative manufacturing options affect optimal transition strategy.
4.2 Extent of Material Transition

An alternative analysis can be developed with a different framing of the material substitution problem. Instead of trying to identify optimal timing, we can start with the assumption that the timing of the transition has been fixed, and instead examining the question of how much material transition is most beneficial. This question seems silly if only a switch of the complete design is considered. However, partial component-wise transitions provide the opportunity to validate market acceptance for new material concepts, overcome the initial cost peak, test materials in practice, adapt mature manufacturing processes to new material properties, and create incentives for the material supply industry without boosting market prices.

It is not the case that the degree of lightweight materials can be chosen without constraints. Although modularization as a manufacturing concept has attracted attention in academia and industry (Jiao et al., 2007), requirements for stiffness and weight balance in most cases do not allow swapping single components after the design has been approved. Once assembly lines have been adapted to engineering requirements imposed by the new vehicle design and the roll-out is initiated, the design is fixed and it becomes nearly impossible to make changes. Therefore, the decision about the rate of lightweight materials has to be made long before the new design is actually fabricated and real cost data is available.

Lightweight materials are only attractive due to their low weight. Most of the other properties that come along with their lower density compared to steel are obstacles to their use. This means that the total benefit is nearly a linear function of the mass of steel replaced with lightweight materials. If material transitions comprise fewer components, benefits are reduced. The interesting question is whether production costs correlate with the mass of material replaced. If this is not the case, there might be a partial transition strategy that would minimize production costs over total weight savings for lower costs per vehicle compared with a full transition.

This case study is an attempt to better understand the relationship between production costs and the rate of lightweight materials in a new vehicle design.
4.2.1 Overview

The base case is a full material transition on both production lines in the plant. Both steel vehicles are replaced by MMLV designs. The costs of this full material transition are taken as a basis for the analysis. In each scenario, more components are assumed to remain unaffected by the transition and are not replaced by lightweight counterparts. As fewer components are swapped with lightweight versions, the amount of aluminum in the MMLV design decreases. The resulting vehicle becomes in fact a combination of steel and MMLV components. This does not mean that components of both vehicle designs could actually be combined in exactly the fashion employed in the analysis. This mixed vehicle is an approximation of independent MMLV designs with a lower fraction of lightweight materials.

![Diagram showing material transition](image)

**Figure 16. Case study 2 – Extent of material transition.**

Notes: A partial material transition allows for a higher degree of resource sharing across production lines (intratemporal) and periods (intertemporal). Investment carry-over increases (3b) as more steel joining methods remain unchanged and equipment does not have to be replaced. Vehicles are more similar in the intermediate period, so that opportunities for intratemporal resource sharing expand (3a). Also the degree of intratemporal sharing in the final period (5) may be affected.

A higher fraction of steel components in the lightweight MMLV design would have two effects: cheaper steel joining methods can be applied in the final state after the transition, and more joining equipment can be carried-over and does not have to be replaced (Fig16-3b). This decreases transition costs and variable production cost at the same time (Tab 4). The intermediate state after the first change-over is typically characterized by high production costs and inefficiencies as two vehicles of different materials are produced on neighboring
production lines. If more steel components remain unchanged compared to the full material transition, vehicles in the intermediate state become more similar and resource sharing provides the opportunity to decrease costs (Fig. 16-3a).

4.2.2 Structure

Table 4 presents the cash flows and output rates of five different transition scenarios, computed by the transition cost module and taken as a basis for the further analysis. The Full Transition scenario is the base case for this case study. Step by step, more steel components are assumed to remain unaffected by the transition. The table presents cash flows for four different partial transition scenarios. For each partial transition scenario, the deviation of total variable costs and capital costs from the full material transition is shown. All results presented in Fig. 17 are based on the cash flows in Tab. 4.
Table 4. Cash flows of second case study.

- Full Transition (base case) -

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<th>Total Var.</th>
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- front structure does not change to MMLV -

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Diff. from Full Transition* (T$) -8,553 -10,761 -8
- per car ($) -6 -8

- front structure, front floor do not change -

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Diff. from Full Transition* (T$) -13,948 -18,132 -13
- per car ($) -10 -13
4.2.3 Results

Figure 17 summarizes the results of this case study. The table in Fig. 17 presents weight savings and transition unit costs of the MMLV design for five different transition scenarios. These assembly unit costs were generated by applying Eq. (8) to the cash flows presented in Tab. 4 for each of the five scenarios. Static unit costs are calculated with Eq. (7) and only take the final production state into account, not the transition path. Two bar charts illustrate the cash flows for the full material transition and for an exemplary partial material transition.

*Cash flows were discounted before taking the difference (r=6.1%)
(see Tab. 4 for details). The adjoining scatter plot relates cost figures to respective weight savings.

4.2.3.1 Cost Assessment

A higher number of unchanged steel components leads to a lower fraction of joining equipment which needs to be replaced. Carry-over of investment (intratemporal sharing) reduces additional capital needs compared to the Full Transition scenario. Table 4 reveals that the more steel components remain unchanged compared to this base case, the lower are the total capital costs for the transition.

Furthermore, an increasing fraction of steel components in the final vehicle after the transition means that more steel joining methods can be used. As steel joining methods are often cheaper than joining methods required for aluminum, total variable costs also decrease. These both effects lower transition unit costs for partial transitions compared to the Full Transition scenario. The table in Fig. 17 shows that unit production costs decrease as the fraction of remaining steel components increases.

4.2.3.2 Cash Flow Analysis

As already discussed, the full material transition requires capital-intense investments in periods five and eight (53,278,000$ and 47,475,000$; compare with Tab. 4). The amount that would be needed to balance the accounts accumulates over time and becomes larger than the initial investment. In contrast, a partial transition requires less capital in transition periods (19,317,000$ and 19,347,000$; compare with Tab. 4), so that outstanding liabilities can be redeemed over time. As already discussed, variable assembly costs are much lower for a partial transition in the intermediate and final state due resource sharing and the application of cheaper steel joining methods. In the final state, variable costs are decreased by nearly 30% (from 51,316,000$ to 36,089,000$; compare with Tab. 4).

A static cost assessment captures the effects of a higher fraction of steel joining methods and a higher degree of resource sharing in the final state. However, the benefits of carry-over of investment from previous manufacturing states are not considered in the static approach. As these effects additionally become cost effective in the transition cost modeling approach, transition premiums react more sensitive to the rate of change as static premiums do.
4.2.3.3 Cost-Benefit Analysis

As previously mentioned, it is obvious that costs decrease if fewer components are replaced by more expensive lightweight versions. Therefore, costs have to be analyzed relatively to the benefits that can be realized. This is done in the table in Fig. 17. Cost per benefits can be expressed as $ per kg reduced.

For the different scenarios presented in this case study, cost premiums were calculated. Cost premium means here the difference between MMLV unit costs for each of the material transition scenarios and unit costs of the steel vehicle. The respective MMLV unit costs are shown in the table in Fig. 17. As a steel reference state, the facelift scenario shown in Fig. 15 is used. This calculation gives five different MMLV cost premiums, one for each of the different transition scenarios presented.

In a second step, these cost premiums were divided by the respective weight savings (see table in Fig. 17), which can be realized in each of the transition scenarios, and plotted as a function of the degree of intertemporal sharing. Intertemporal sharing is used as a continuous representation of discrete design changes between these different transition scenarios. Results are shown on a relative scale with maximum costs equal to 1.

4.2.4 Discussion

First of all, it depends on the boundary conditions how many steel components should be swapped with lightweight versions. It makes a big difference if the guideline is to reduce the weight by x% for the lowest cost possible, or to reduce as much weight as possible for the fixed amount x.

Assuming that the cost-efficient solution is targeted, it is still not clear how weight can be reduced most economically. Compared to a full material transition, assembly unit costs per vehicle decrease as the need for more expensive aluminum joining processes diminishes. Tab. 4 shows this clear relationship. However, if the metric to compare different scenario is not total cost but cost per weight reduction ($/kg), this clear trend disappears. While the benefits of different components being swapped with lightweight versions can be determined easily, the costs are more difficult to estimate.

Required types of joining methods, number of connects, their accessibility, etc. are different for each component and together affect the respective change penalty, which has to
be paid to switch the material. Components’ manufacturing requirements can both promote and hinder a material transition.

Additionally, there are interrelationships between single components. Changing the material of one component could impose structural requirements on another, leading to higher total transition cost. In order to find an analytical solution which components make most economic sense to be replaced, costs and benefits would have to be assessed for each possible combination of components being swapped. Given the number of parts in a vehicle, there is a nearly unlimited number of ways how a certain level of weight reduction can be realized.

The likelihood of components being swapped with lightweight counterparts is assumed to depend exclusively on structural requirements. Discussions with Ford Motor Company suggest that it is more difficult to switch components which are more crash-relevant. For this case study, it was assumed that crash-relevance determines the order of components being replaced. Once this artificial order is fixed, the problem is reduced to one dimension, so that costs and benefits can now be analyzed as a function of one variable, the extent of the material transition.

The plot in Fig. 17 presents the relationship between costs per weight savings and the degree of intertemporal sharing, which is taken as a continuous representation of unchanged steel components. Results show that there might be two points, where costs per weight savings ($/kg) reach local minima. If a company aims at reduced costs per unit compared to a full material transition, it seems beneficial in terms of $/kg to swap the underbody with the aluminum version but to keep the steel front floor in place. Design data helps to explain this behavior.

On the one hand, the number of connects required to assemble the MMLV underbody (excluding the front floor) is drastically reduced compared to the steel version due to part integration, on the other hand a higher number of different types of joining methods and more expensive joining equipment is needed. For example, more adhesive bonding is used instead of spot welding. Consequently, costs per connect are much higher for the MMLV underbody but a lower total number of connects can partially compensate this cost increase.

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10 Aluminum is softer than steel and characterized by a lower crash performance.
This lower number of connects also translates into less joining equipment needed for the MMLV version.

The result is that the additional capital required to switch to the assembly of a lightweight underbody is rather small. Given the potential weight savings and compared to other components, it would not make sense to keep the steel underbody in place if the goal is to optimize the $/kg ratio.

The case study shows that some configurations of a partial transitions might have the same benefits (in terms of $/kg) than a full material transition but lead to considerably smaller costs per unit. Excluding only those subassemblies from the material transition, which have higher change penalties, can be beneficial for a carmaker who favors a partial component-wise transition due to reduced costs per unit.
Figure 17. Transition costs depend on the extent of material change.
4.3 Platform Sharing

Manufacturing flexibility has potential cost-effective benefits if it improves the system’s ability to adapt to adverse changes in the environment. Resource sharing can be seen as an opportunity to bring more flexibility into a manufacturing system. Furthermore, sharing has direct effects on the production process.

Shared resources, e.g. programmable tooling, have an increased utilization rate. This might reduce the total number of tools needed and, additionally, has the potential to decrease the fixed cost portion of unit costs.

However, flexible tooling is more expensive per unit and potentially increases total capital costs. It requires slower production rates to accommodate the differences in robotic action required for different vehicles. The increase in cycle time means a reduction in throughput. Furthermore, if flexible tooling can handle components for different vehicles, but the joining methods that are applied show a low similarity, than the effective potential to share joining resources is limited.

There is no guarantee that cost decreasing effects of sharing can offset the loss in process efficiency and higher capital costs. It depends upon the conditions of its application. One of the most important variables is the similarity of components’ manufacturing requirements. The penalties that have to be paid to make machinery compatible to different components depends to a large part on the variance of process requirements imposed by these components.

This case study analyzes the relationship between resource sharing, flexibility, and unit costs to better understand when sharing and flexibility make economic sense.

4.3.1 Overview

For this case study, platform sharing means that front structure and underbody components for both vehicles in the plant are assembled on the same stations, using flexible tooling. Platform sharing among both steel vehicles is realized in the initial state (Fig. 18-1) and the carmaker also intends to implement platform sharing among MMLV designs (Fig 18-5) once both changeovers are completed.

If the decision is made to switch to the production of MMLV-type vehicles in period 4, most of the joining equipment and tooling needs to be replaced. It is assumed that there are
two options per subassembly as to which kind of new tooling can be implemented: (a) flexible tooling that is compatible with both steel and MMLV platform components; (b) tooling that is only compatible with MMLV platform components.

If option (a) is realized, resources can already be shared in the intermediate period across different vehicle types and tools are assumed to only be slightly adjusted after the changeover of the second production line. In the case of option (b), tools are less expensive but cannot process steel components and do not allow sharing in the intermediate period.

Once the second changeover is completed and equipment and tooling of the second production line has been replaced, platform sharing among MMLV designs is implemented for both options.

The degree of resource sharing in the intermediate period is described by the intertemporal sharing ratio (Fig. 18-3a).

![Diagram](image)

**Figure 18.** Case study 3 – Platform sharing.

Notes: In the initial and final transition periods, when two highly similar vehicles are produced on neighboring production lines, platform sharing is assumed (front structure, underbody). In the intermediate period, two different vehicle types are produced in the same plant. In this case, intermediate intratemporal sharing across vehicle types, represented by (3a), would mean that tools need to be able to handle components for both different vehicle types.

The initial and final state is characterized by platform sharing, and all other joining activities applied to non-platform components are unshared in all states. Joining activities for platform-components are grouped into five subassemblies. For each of these five subassemblies, production costs were sequentially computed and evaluated to establish whether it makes
economic sense to implement sharing (a) in the intermediate period among different vehicle types, or (b) only in the final period.

4.3.2 Structure

This case study is built around six different scenarios. Table 6 shows the underlying cash flows for each of them. The first scenario is based on the assumption that no resources are shared in the intermediate state (Fig. 18-3a). It is used as a base case for the further analysis. In every further scenario, labeled I-V, equipment and tooling for another platform component are assumed to be shared across vehicle types. In the initial and final period, when only two equal vehicle types are produced (two steel vehicle and two MMLV, respectively), platform sharing is implemented. Table 5 summarizes the assumptions regarding resource sharing for the five different scenarios.

Table 5. Transition strategies and intermediate intratemporal platform sharing.

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<th>Subassembly</th>
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<th>Intermediate State</th>
<th>Final State</th>
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<td>x</td>
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<td>underbody w.</td>
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<tr>
<td>others</td>
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Notes: Joining activities for platform components (front structure and underbody) are grouped into five subassemblies. Platform sharing is implemented in the initial and final period (x=shared). Non-platform joining activities are not shared. Five independent scenarios were computed (I-V), each considering one of the platform subassemblies as shared in the intermediate state.

Furthermore, Tab. 6 presents the difference in total variable production cost and capital cost between each of the scenarios I-V and the base case scenario (No Sharing). All results presented in Fig. 19 are based on the cash flows in Tab. 6.
Table 6. Cash flows of third case study.

**- No Sharing (base case) -**

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**- front structure (I) -**

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Diff. from No Sharing* (T$)  
- per car ($)  

**- front floor (II) -**

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Diff. from No Sharing* (T$)  
- per car ($)  

78
### floorside rear (III) -

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Diff. from No Sharing* (T$) 271.28 5612.77
- per car ($) 0.19 3.92

### UB asm. complete (IV) -

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Diff. from No Sharing* (T$) 304.75 -230.68
- per car ($) 0.21 -0.16

### UB w. lower back (V) -

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Diff. from No Sharing* (T$) 442.68 162.58
- per car ($) 0.31 0.11

*Cash flows were discounted before taking the difference (r=6.1%)
4.3.3 Results

Figure 19 summarizes the results of this case study. The table in Fig. 19 presents intermediate intratemporal sharing ratios (Fig. 18-3a) and MMLV transition unit costs for each of the scenarios I-V, each considering one of the platform subassemblies as shared in the intermediate state. The base case of no sharing in the intermediate state is also shown. Furthermore, the table lists nominal capital costs of the first and second changeover. These numbers can also be found in Tab. 6. The bar charts in Fig. 19 illustrate cash flows over the ten-year period for the base case with no sharing in the intermediate state and for scenario II with shared front floor operations. The scatter plot pictures the relative change of capital costs and total variable production costs for scenarios I-V relatively to the bases case scenario.

4.3.3.1 Cost Assessment

The table shows that only the scenario II with a shared front floor yields lower unit costs than the base case scenario. A shared front floor in the intermediate period reduces MMLV unit costs by 0.4%. Resource sharing for other subassemblies increases unit costs. The cost effect is independent of the degree of intertemporal sharing (only 13% for the front floor). Capital costs for the first and second changeover vary. A shared front floor leads neither to the lowest capital costs for the first (60 M$) nor for the second (45 M$) changeover, but it minimizes the sum of both (105 M$).

4.3.3.2 Cash Flow Analysis

The bar charts show that a shared front floor in the intermediate state leads to increased capital costs for the first changeover compared with the base case (from 58,291,000$ to 60,138,000$; compare with Tab. 6). Flexible tooling, which can process both the MMLV and steel front floor, is more costly. Although the utilization rate is increased and a lower total number of tools required, the higher costs per unit still dominate.

Variable production costs of the MMLV are slightly reduced in the intermediate state, from 28,403,364$ to 27,642,102$. This is mostly a consequence of lower overhead and labor costs per vehicle. Labor costs are decreased because of a higher labor utilization rate for a shared front floor and overhead costs due to economies-of-scale.
Implementing flexible tooling in the course of the first changeover reduces capital costs of the second changeover; in this example from 51,084,740$ to 44,828,668$. The reason is that the flexible tooling for the front floor can already handle MMLV components, so that there is less dedicated equipment which needs to be replaced in the course of the second changeover when platform sharing is implemented again.

4.3.3.3 Cost-Benefit Analysis

The data points that are plotted in the adjoining scatter plot can be found in Tab. 6, which presents the difference in total variable production costs and capital costs (both discounted) between each of the scenarios I-V and the base case scenario. The scatter plot presents this deviation of variable and capital costs from the base case for each of the scenarios. The scale is relative with the cost of the base case as the reference point. The plot illustrates why the front floor (scenario II) is the only component where sharing leads to reduced unit costs. A shared front floor reduces at the same time capital costs and total variable production costs (-279,970$ and -2,521,460$; compare with Tab. 6). For all other platform components, sharing would result in higher variable production costs. Only scenario IV leads at least to reduced capital costs (-230,680$; compare with Tab. 6).

4.3.4 Discussion

This case study illustrates how many variables affect the costs and benefits of resource sharing. The transition strategy in this example is reduced to only one decision – what kind of tooling should be implemented in the intermediate period – but underlying cost effects have still not lost their complexity.

4.3.4.1 Front Floor

The front floor appears to be the component where sharing in the intermediate state makes most economic sense because, according to the process-based cost model, this component seems to be particularly suitable for sharing for the following reasons.

Both front floor types, for the steel and MMLV design, are partly joined with projection welds, so that flexible tooling can feasibly be used to share projection welding equipment. This processing compatibility is not the case for all platform components.
Both front floor types have a similar welding count, which cannot be said for all subassemblies. A similar welding count leads to higher efficiency and utilization of shared equipment because the total cycle time is equal for both component types.

Both front floor types are held together by spot welds. Spot welding equipment cannot be shared across vehicle types due to the differing processing configurations needed between steel and aluminum (see 2.5.2 for details). However, spot welding equipment is relatively inexpensive, so that the sharable equipment, for projection welding, is more expensive than the non-sharable equipment.

Nevertheless, greenfield capital costs would still be slightly increased for a shared front floor in the intermediate state, when compared to the base case. Total capital costs are only reduced because the expensive flexible tooling (60,138,000$; compare with Tab. 6) implemented in the course of the first changeover decreases capital cost of the second changeover (44,829,000$; compare with Tab. 6).

4.3.4.2 Manufacturing Flexibility

In this transition scenario, resource sharing was used to introduce product flexibility and process flexibility into an existing manufacturing system. Consequently, capital costs of the first changeover were increased compared to the base case. If costs in the intermediate period are analyzed independently, e.g. with a static cost model, a shared front floor would not be economically reasonable. Reduced variable costs (mainly lower labor costs), cannot offset the higher costs for equipment (more equipment needed due to slower cycle times) and tooling (higher unit costs of flexible tooling).

However, this product (material) flexibility became cost effective in period eight, when the ability “to changeover to produce a new (set of) product(s) very economically and quickly” was needed (Brown et al., 1984). Taking this cost effect into account, a shared front floor in the intermediate period decreases MMLV transition unit cost.

Also process and volume flexibility was increased when flexible tooling was implemented. These benefits could not be quantified because the model is purely deterministic. Still, both types of flexibility are beneficial for the carmaker and make the manufacturing system more resilient. When process and volume flexibility are considered, other scenarios might also make economic sense. For example, scenario IV only results in a
marginal increase of unit costs but a high intertemporal sharing ratio. This means that the value of shared resources is high and the system's intrinsic level of process and volume flexibility increased.

4.3.4.3 Further Strategic Implications

There are other arguments why resource sharing across different vehicle types in the intermediate state could make sense. Compared to the base case, scenario IV leads to increased (discounted) MMLV unit costs due to higher variable production cost (per vehicle, 0.21$; compare with Tab. 6) while at the same time (discounted) capital costs are slightly reduced (per vehicle, -0.16$; compare with Tab. 6). If variable costs are preferred to capital costs, scenario IV could be attractive for the carmaker.

Furthermore, intermediate resource sharing shifts more capital to the first changeover and lowers capital costs of the second changeover. For this study, a discount rate of 6.1% was assumed, but a lower discount rate could favor earlier expenses.

All these strategic arguments need to be considered when searching for the optimal transition strategy.
Figure 19. If sharing makes economic sense depends upon the conditions of its application.
Chapter 5 – Discussion and Conclusion

In the preceding chapter, different cases were presented to address the three basic questions facing a carmaker who intends to replace steel with lightweight materials – when, to what extent, and how. Each of the cases focuses on one specific question and applies a coherent set of assumptions grounded in current technical practice. These assumptions help to zero in on a particular aspect of the decision problem, narrowing the scope of the analysis from the nearly unlimited number of other effects which impact the outcome of a real decision process.

This chapter is an attempt to broaden the perspective again and approach the problem of material transitions detached from this strict modeling framework. Results of the case studies are used to discuss costs of material transitions in a general (chapter 5.1) and case-specific context (chapter 5.2), and motivate an Extended Transition Modeling approach (chapter 5.3).

5.1 Change Penalties

A product and its respective manufacturing system are closely related. Changing the product design almost always means that the manufacturing system also needs to be adjusted. When this is the case, design changes are accompanied by change penalties. These change penalties can be segregated into three different sub-classes.

5.1.1 System-dependent Change Penalties

In chapter 2.5, interdependencies among materials and joining technologies were discussed. Joining technologies exploit specific material properties to join two different components. In most cases, these joining technologies are effective for only a small range of material properties. If properties change within the expected boundaries, e.g. for different types of steel, joining methods are still applicable. However, if a more aggressive material change is desired (for example, the group of materials is switched from ferrous metals to noble metal), the incumbent joining technologies will no longer be applicable.

In the case of body assembly facilities, most investment is spent for joining equipment. Therefore, most investment expects a narrow range of material properties. When the base material is switched, joining equipment needs to be replaced. Replacing machinery before its end of life leads to a capital loss, since the salvage value is nearly always lower than the remaining book value. This capital burden can be regarded as change penalty of the
manufacturing system. The lower the change penalties are, the higher the intrinsic level of product flexibility. One could say that material-related product changes are by nature strong influences on the capital costs of assembly-based manufacturing systems.

5.1.2 Material-dependent Change Penalties

A product is, in most cases, made of the material which is regarded as the most suitable candidate from the perspective of performance, processing, and cost. If the product design (including material) has reached a certain level of maturity, as it is the case for the automobile although its market is open for innovation and change, there probably are material alternatives that the firm must evaluate for use. If a material change suddenly becomes attractive, it is fair to assume that some aspects of the surrounding system have changed, such as political or regulatory market conditions.

In contrast to computational models, changes in the real world are often a result of continuous processes. Although there is considerable dynamism in large scale product manufacturing, wholesale change at the core material level happens rarely, because the rate of change in product and process tends to move incrementally. As a consequence, it is rarely the case that a firm will be influenced by so many technical, economic, and regulatory changes at once that suddenly another candidate material is better in all aspects. Materials transitions typically play out in a trade-off space between the attractive features of a material alternative which may (or may not) compensate other less attractive features. Thus, the decision-maker needs to trade off the new material against the material currently in use. If the decision is made to apply the new material in order to benefit from the more attractive features, it is often the case that less attractive features create obstacles which have to be overcome. This phase of trial-and-error and engineering-based problem solving increases time-to-market and generates cost. One example could be temporally increased inspection costs after the transition from steel to aluminum due to the lower hardness of aluminum. Therefore, material-related product changes nearly always lead to technological challenges and material dependent change penalties.

5.1.3 Path-dependent Change Penalties

Given that a system has a generally agreed-upon metric of optimality, e.g. production cost, and it can be optimized regarding this metric and according to current boundary conditions,
then a shift to other boundary conditions often implies that another state is optimal. A transition towards this new optimal state nearly always means that the system has to overcome non-optimal intermediate states – certainly true for material transitions.

If a material is replaced by an alternative material, it not only takes effort, but also time to adjust the manufacturing system to new requirements. This temporary phase between initial and final manufacturing state, here called intermediate state, is often non-optimal due to a number of restrictions imposed on it:

**Engineering capabilities:** During intermediate states, the carmaker needs to maintain a wider range of engineering capabilities along the full value chain to meet combined engineering requirements of both materials (e.g., quality testing equipment for both materials is needed)

**Economies-of-scale:** Economies-of-scale are limited due to a divided production volume and economies-of-scope cannot fully compensate this effect.

**Learning-by-doing:** Incremental improvements are realized through learning-by-doing. As intermediate states are also temporally intermediate states, improvement through learning-by-doing is limited.

Real manufacturing systems are never in their theoretically optimal state. Still, there are manufacturing states which are seen as optimal and strived for by decision-makers. The path over non-optimal intermediate states leads to a further path-dependent change penalty. This penalty depends on the path that is taken, as well as the degree of non-optimality of intermediate states.

These three different change penalties make up the costs that have to be paid to implement material changes into products and, indirectly, manufacturing systems. Therefore, material transitions are characterized by different dynamic cost components, which would be ignored if only the final manufacturing state is analyzed. Although the transition cost model applied in this study is a great simplification and does not take the entire cost effect of change penalties into account, it sheds light on a critical aspect of material transitions. The cost results which have been presented in chapters 4.1 and 4.2 are summarized in Fig. 20. The numbers reveal that a transition towards an aluminum-intense multi-material vehicle is more
expensive than a greenfield production of the same vehicle. This difference between greenfield and transition unit costs is the direct consequence of change penalties.

5.2 Material Transition

5.2.1 Cost

In Fig. 20, two different material transition strategies, a full transition and a partial, component-wise transition, are related to two different steel reference scenarios, a facelift and a redesign. Unit assembly costs generated with the static and dynamic cost assessment approach are shown. Since these are the results of case studies presented in chapters 4.1 and 4.2, which were based on strict assumptions, cost figures can only be used to better understand general trends and magnitudes, rather than relying upon the absolute values.

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<th>Steel Facelift</th>
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<td>2.5 $/kg</td>
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Figure 20. Cost matrix for transition strategies.

Notes: The table summarizes results presented in previous chapters (for assumptions, see respective case studies).

On the one hand, results reveal that the aluminum-intense design is rather expensive to fabricate, given that the company would have to switch their entire manufacturing system. For the full material transition, change penalties increase greenfield MMLV unit costs by 51$ from 460$/unit to 511$/unit. This shows that change penalties are critical to material strategies. Partial component-wise transitions of only suitable subassemblies, leaving steel subassemblies with the highest change penalties in place, might be an opportunity to lower
change penalties. In this example, change penalties of a partial transition increase greenfield MMLV unit costs only by \(26\) from \(374\) to \(400\).

On the other hand, assembly unit costs of the alternative steel vehicle are also increased if design changes and change penalties for the steel scenario are considered. In this example, change penalties, which need also be paid for a steel facelift, increase greenfield unit costs by \(34\) from \(275\)/unit to \(309\)/unit and for a complete structural redesign even to \(335\)/unit. High change penalties in the alternative steel scenario make the material transition more attractive.

In sum, the economic viability of a materials transition depends on both greenfield production costs of the lightweight and conventional vehicle, as well as the difference in change penalties for both scenarios.

5.2.2 Flexibility

Chapter 4.3 presents a strategy to reduce change penalties by introducing product flexibility into the manufacturing system. Preparing the system for a later material transition was shown to be beneficial if the flexibility is actually needed at a later point in time, so that it becomes cost-effective.

It should be noted that material flexibility is not the same as product flexibility; it is more a sub-element of the concept. Since every material transition also involves a product change, product flexibility, in the form of programmable tooling, has the potential to make the transition more economically reasonable. However, there are further strategies which also could increase the system’s ability to switch the base material. The case study in chapter 4.3 shows that lower change penalties can be reached (for the front floor; chapter 4.3.3) if the current subassembly and the new lightweight subassembly use the same type of joining technology. This suggests that joining technologies, which are known to be versatile and adjustable to potential future base materials, could be used for the next steel design in order to prepare the manufacturing system for a later material transition. This result suggests that the steel vehicle could be designed to exploit this opportunity. Considering a future transition to a lightweight material already in the assembly requirements of next steel design could add advantage.
5.3 Extended Material Transition Modeling

Greenfield unit costs presented in Fig. 20 capture the difference in production costs and capital costs for both different vehicle types. However, change penalties, which occur if the product design is changed so drastically that the manufacturing system needs extensive adjustments, are omitted in the calculation. That these penalties are critical for the economics of material transitions has been shown. This chapter attempts to discuss a further aspect of material-related engineering changes, which could be considered in a future extended transition cost modeling approach.

The bitemporal transition modeling approach applied in this study is based on the general understanding that the initial and final states of the manufacturing system are fixed due to engineering requirements imposed by vehicle designs. Only the path between both states is assumed to be subject of the optimization. The range of possible paths depends on the characteristics of initial and final states but which of those is optimal is only a function of boundary conditions.

However, it has to be realized that, for real material transitions, only the current (initial) manufacturing state and, if anything, the future (final) vehicle design is fixed. This future vehicle design determines the engineering capabilities which need to be provided by the manufacturing system, but it does not determine the manufacturing state itself. There is still a range of manufacturing strategies, in terms of resource sharing, which all allow fabricating the vehicle according to requirements. Each manufacturing strategy would lead to different production cost and change penalties. Since there might be a trade-off between the optimality of the final manufacturing strategy and the optimality of the transition path required to realize this manufacturing strategy, both could be considered in an overall cost optimization.

An extended transition cost model could consider the actual manufacturing strategy (and perhaps even the vehicle design) in the final state as a further variable of the cost optimization.

5.4 Conclusion

This thesis makes clear that the concept of transition penalties and resulting total transition costs is critical to material transitions. The optimality of transition strategies depends certainly on the production costs in the final state (greenfield approach), but to a large part
also on the transition costs generated during the conversion to this state. Effective unit costs are a function of the costs of the transition path and previous manufacturing states (path dependency).

It was shown that these transition costs can be decreased by implementing material flexibility, by realizing a component-wise conversion, and simply the right timing. Focusing independently on each of the different sources of transition cost presented in chapter 5.1 could contribute further ideas.

Weight reduction strategies should be assessed with respect to the effort that needs to be expended to realize them, recognizing the realities of current automotive manufacturing systems. Applying the Transition Cost Modeling approach presented in this thesis could be a step in this direction and add value.
References


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Appendix

A. Transition Unit Cost – General Form

The general form of Eq. (9) is given as

\[ C_{\text{trans}} = AN \left[ \left( \frac{\alpha}{t_1-e} \right)^2 + \beta t_1 - e \right] + \gamma t_2 - e + \frac{\lambda_{\text{trans}}}{(1+r)^{t_1-t_1+1}} + \sum_{t=t1,...,e} \frac{C_{\text{par}}}{(1+r)^{t-1-t_1}} \],

with year of first transition, \( t_1 \), year of second transition, \( t_2 \), equipment lifetime (scenario length), \( e \), year, \( i \), discount rate, \( r \), combined production output per year, \( Y_i \), initial investment, \( I_{\text{steel,initial}} \), capital costs of the first transition, \( I_{\text{trans}}^{\text{trans}} \), capital cost of the second transition, \( I_{\text{trans}}^{\text{trans}} \), and total variable production cost per year, \( C_i^{\text{var}} \). Operators \( \beta t_1 - e \) and \( \gamma t_2 - e \) adjust the transition cost, \( I_{\text{trans}}^{\text{trans}} \) and \( I_{\text{trans}}^{\text{trans}} \), to the fraction that is paid off before the end of the \( e \)th period. The operator \( \alpha^\frac{0-t_1-1}{t_1} \) has the same function. It adjusts the initial investment to the fraction that is paid off between year \( t_1 \) and year \( e \) and discounts these partial investment cost to period \( t_1 - 1 \).

B. Transition Unit Cost – Accounting Methodology

Figure 21 presents an example spreadsheet to illustrate the accounting methodology which is used to generate transition unit costs.

1) Initial investment is spent to set up the plant infrastructure.

2,3) In the course of the first and second changeover, some fraction of the equipment needs to be replaced and new capital is needed. If the replaced equipment has salvage value, it generates return.

4) The sum of salvage value and additional capital requirements gives total transition costs.

5) In the greenfield approach, initial investment costs are annuitized over the respective lifetime.

6) In the transition cost modeling approach, annuities in years before the transition remain unaffected by the transition.

7) Transition costs are annuitized over the respective lifetime of the new equipment.

8) For the regarded time period, the net present value is calculated.
9) This net present value is annuitized and again spread over the regarded time period. This gives net annuities which can be put in context with respective production rates.
### Case Details

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1. Trans: -$40,000
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### Greenfield Approach

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**NPV**

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**NPV**

**Net Annuities**

### Figure 21. Overview of Transition Cost Accounting. 