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# On Material Substitution in Automotive BIWs – From Steel to Aluminum Body Sides

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## Abstract

Weight reduction and material substitution are increasing trends in the automotive industry. In this project, the task of substituting the steel body side in the monocoque of a large SUV towards an aluminum body side was investigated through a design engineering approach adopting a breadth-first analysis method. One conclusion based on the analysis is that the choice of joining technology would become arbitrary due to the breadth-first approach. In this paper, the authors present their findings from the aforementioned case, including the challenges with switching between materials with fundamentally different properties when performing material substitution projects. The possibility of having taken a depth-first analysis approach, and the possible effects on the project result, is discussed.

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## 1. Introduction

The weight of the Body in White (BIW) of a car has a substantial impact on the weight of the finalized vehicle. The body in itself, using traditional material like steel, account for 40% of the total weight of the vehicle [1] and a lighter body enables weight reductions in other areas of the vehicle (for example the use of a smaller engine) while keeping the same product performance [2]. At the moment, automotive companies have presented different ways of reducing weight in BIWs via introduction of new, more light-weighted materials and manufacturing technologies, but have not converged into a single most preferable solution. Approaches for reducing weight in a BIW include carbon fiber reinforced polymers (CFRP) [3, 4, 5, 6], aluminum [7, 8, 9], an increased usage of high-strength boron steels [10] and combinations of these approaches.

Another distinction important to make when looking at weight reduction projects within the automotive industry is the one between substitution projects and major redesign or new product development (NPD) projects. Substitution projects are

where one or a few components are substituted for similar components in other materials with no or very little change to adjacent components in the finalized vehicle. Major redesign or NPD projects are when most of the body is redesigned and the new materials are included early in the design process. These two different types of projects will have very different boundary conditions, and outcomes in terms of plausible results.

Given these qualities, it is relevant to evaluate whether substitution projects could generate applicable results in weight reduction projects involving material substitution. Earlier projects have been done on this, approaching the project from a material technology standpoint [11] and an economic standpoint [12], but the design engineering approach appears under-researched at the moment. Therefore, this case was evaluated from a design engineering approach.

The aim of this paper is to identify challenges with substitution projects when introducing new materials in automotive BIWs, using a design engineering-based approach. Also, since the new Volvo SPA platform includes aluminum

components [13], the project focused on a switch from a steel to an aluminum body side.

## 2. Theory

Material substitution in existing car bodies affects both product development and production processes in an integrated way. This is even more challenging in an automotive industry that manufacture vehicles in a Mixed-Model Assembly (MMA) line, where different generations of vehicles are produced after each other in a balanced flow. Sequencing vehicles with increasingly different content and with different time consumption in assembly is challenging with regards to total manufacturing time for each vehicle [14].

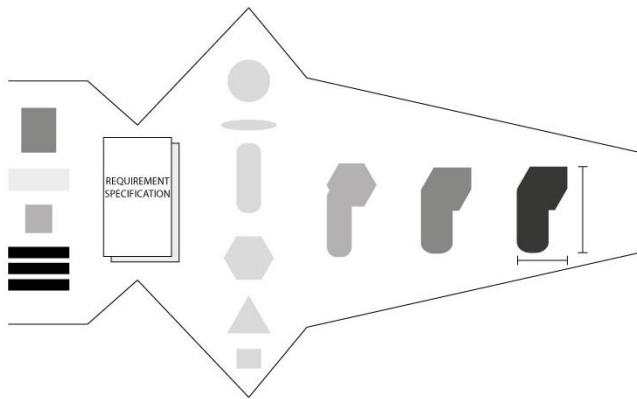


Fig. 1 The generic product development process according to Ulrich and Eppinger [15]. A project progress through the process from left to right, from customer input to a designed and tolerance final product.

### 2.1. Product development theory

Product development, while always somewhat iterative, is often displayed as a linear activity (as seen in Fig. 1) [15], where needs are assessed before any concept generation is initiated. The product development process consists of the following activities [16]:

- Needs assessment
- Problem formulation
- Abstraction and synthesis
- Analysis
- Implementation

Design problems are usually ill-defined, meaning that they lack vital information to solve the problem analytically and that the end goals are often vague [17]. As a consequence, formulating the problem is considered a vital task in product development projects [16]. This encourage cross-functional teams, since these teams increase quality in high-risk NPD projects [18]. Also, since all product development projects include constraints defined early in the process [19], a diverse set of competences early on increases quality in the problem formulation.

Evaluating design solutions, a part of the analysis activity, can be done in a number of different ways, from completely

arbitrary to completely quantified [17]. Usually, a combination of methods is used for this task.

According to Ulrich and Eppinger [15], the success of a product development project could be evaluated on at least five different qualities:

- Product quality
- Product cost
- Development time
- Development cost
- Development capability

While the first four are established and quantifiable to some extent, the fifth quality, “development capability”, is not as self-evident. This quality is a measurement of the knowledge gathered in the project, and how easily it can be put into future use for increasing the four first qualities of a product development project (product quality and cost, and development time and cost). [15]

### Breadth-first vs. depth-first analysis

The “abstraction and synthesis” and “analysis” activities within the product development process could, in a simplified way, be viewed as an algorithm where the development team tries to find the best way through the data tree (i.e. find the best possible product solution out of all possible concepts). Some sort of hierarchy can be described, where some decisions (i.e. levels) depend on earlier decisions (i.e. higher levels in the hierarchy), as can be seen in Fig. 2.

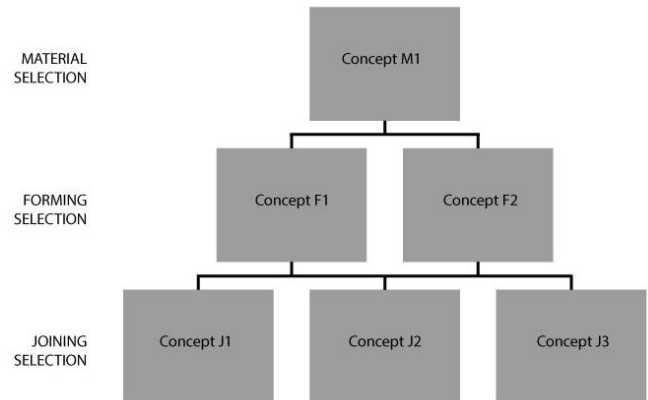


Fig. 2 A hierarchical representation of the selection process in product development. This representation assumes full compatibility between all concepts.

Two distinctly different approaches to this search can be seen: the breadth-first analysis and the depth-first analysis. In a breadth-first analysis (seen in Fig. 3), all possible solutions on a given level is evaluated before the next level in the hierarchy is explored [20, 21]. In product development, this would translate to a linear project where decisions on one level in the design hierarchy were made before continuing to further levels in the design hierarchy.

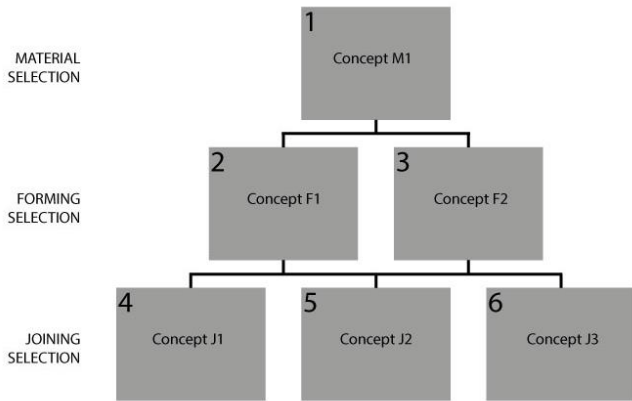


Fig. 3 Breadth-first analysis approach. The numbering denotes in which order the solution will be processed.

In a depth-first analysis (Fig. 4), the idea is to go to the root of the tree before exploring alternatives on the same hierarchical level [20, 22]. In product development, this would translate to a project model where all or several concepts were developed to a great level of detail before the decision on which path to take was taken.

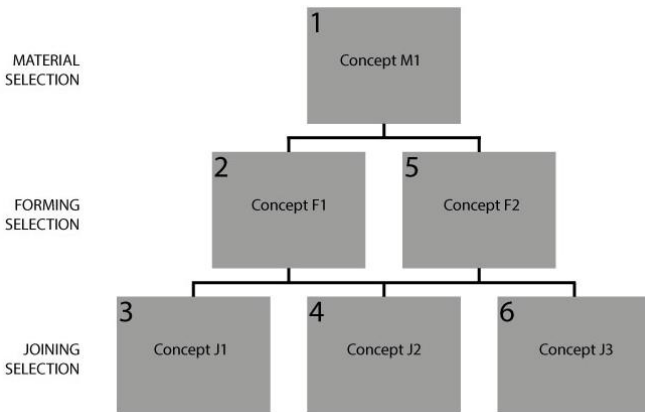


Fig. 4 Depth-first analysis approach. The numbering denotes in which order the solution will be processed.

2.2. Manufacturing an automotive BIW

The automotive manufacturing plant is generally divided in three parts; the body shop, the paint shop and the assembly shop [23]. The BIW is manufactured (formed and joined) in the body shop, painted in the paint shop and then assembled along with all other components to become a finalized vehicle in the assembly shop.

2.2.1. Manufacturing in aluminum

Aluminum components in vehicle bodies are commonly made via either casting, extrusion or stamping [24]. Manufacturing body panels in aluminum via stamping is at the moment more expensive and more difficult than producing the corresponding components in steel, due to die costs, coatings and lubricants and slower stamping rates [12, 24]. Dies also have to be designed with the correct aluminum alloy in mind, since spring-back differs with different alloys [25]. To cope with these challenges, vehicle manufacturers tend to collaborate with materials companies to developed tailored aluminum alloys [26].

2.2.2. On joining in dissimilar materials

In general there are four types of joining processes: mechanical, chemical, thermal and hybrid joints [27].

When joining dissimilar materials such as steel and aluminum, there are a number of different possibilities regarding joining technology, both thermal and mechanical joining processes are used in industry at present [11].

3. Benchmarking of other substitution projects

There has been a trend in the automotive industry to substitute material in existing products, and many substitution projects have been done in the industry over all. These have focused both on manufacturing technology and material substitution, and have included more materials than aluminum.

Earlier projects evaluating aluminum-to-steel welding have concluded that piece-by-piece substitution projects with existing manufacturing equipment is not an optimal solution with regards to end product quality and cycle-times [11], and the same has been found from an economic standpoint since the new materials can seldom be used to their fullest potential when using this approach [12].

Luo [28] presents an analysis of plausible areas for introduction of magnesium components, and emphasizes on the possibilities of creating thinner walls in cast magnesium than in plastics or aluminum.

Holbery and Houston [29] presents possibilities for including polymers reinforced with natural fibers, and show prototypes of load-bearing components such as underbody panels in passenger vehicles that have been made to withstand the demanding environment such components endure.

Earlier work on advanced composites have argued that the combination of advanced composites and traditional metals might have be hard to incorporate in the same vehicle platforms, due to the difference in material qualities and behavior [30].

One other way of substitution is to change the architecture of the vehicle itself, and while that has definite benefits in terms of weight reduction [31] this approach has its own challenges. For example, it seems to be hard to manufacture spaceframe vehicles in the same numbers as monocoque vehicles without greater costs [12, 24].

Summarizing the aforementioned substitution projects (of different approaches), and comparing them to larger light-weighting projects [1, 31, 32], it appears important to understand the differences between new product development

and substitution projects. A distinction between the two different types of projects, and their different qualities, can be seen in table 1.

Table 1. Different kinds of weight reduction projects in BIWs.

Quality	Substitution projects	Major redesign or NPD projects
Changes to BIW	Minor	Major
Effects to the product	Local	Affecting the whole vehicle
Workload in development	Minor	Major
Interaction between expert areas in the design process	Minor	Major
Latest possible introduction in the vehicle lifecycle	Late	Early



Fig. 5 Volvo XC90 MY2015 [37]

#### 4. Methodology

The investigation of product and production development challenges when transitioning from steel to aluminum in a multi material body was done via an analysis of a smaller case study. A case study is used to explain a set of decisions [33]. The case study is a mainly qualitative research method [34, 35], but it can be argued that case studies can be used for quantitative analysis as well [36]. In this case, the study was used as a qualitative method for identifying challenges when introducing new materials in automotive BIWs.

In this case study, the introduction of an aluminum body side on a larger family SUV was investigated. This meant that a redesign of the body side was performed following a simple linear project model (Fig. 6 and Fig. 7), and later evaluated in terms of identified challenges and issues during the project. The project focused on a design engineering-approach, including material, geometry and manufacturing processes in the analysis of concepts [23].

#### 5. The case

The investigated case was designed as a material substitution project switching from high strength steel to aluminum in the body side of a Volvo XC90 MY2015 (Fig. 5)

##### 5.1. Defining the case

Before the case project started, some initial delimitations were set as definitions of the case.

- Focus was set on minimizing the change done to the rest of the car body
- A holistic design engineering approach should be taken, taking material, geometry and manufacturing process into account
- The project would focus on minimizing the change to the production system
  - Previously established forming systems were prioritized
  - One additional workstation for joining the body side was allowed

##### 5.2. Work process

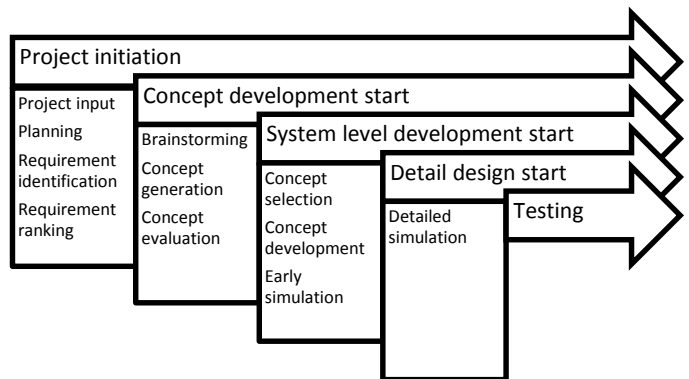


Fig. 6 The working process (starting at the top) of the material substitution project

The main setup of the case project followed the methodology described by Ulrich and Eppinger [15]. The project covers the activities from project initiation until select product concept according to Fig. 6 The working process (starting at the top) of the material substitution project. The project was set up as a breadth-first analysis project to mimic how product development processes are often described in literature.

The requirements were defined via a brainstorming session identifying areas where the proposed solution would be beneficial in comparison to a traditional steel body side. These possible requirements were then evaluated via two sessions of pairwise comparison, in order to minimize biasing risks. The two results were averaged and the five highest scoring requirements were redefined into three main criteria: A fast, energy efficient manufacturing process, a strong material with low costs and a lightweight but strong component.

With regards to these three main criteria, a new brainstorming session was setup. Delimitations to use existing aluminum material and stamping infrastructure were set, and brainstorming was done on joining the body side to the body structure and on the reinforcements used in the body side today.

These ideas were later evaluated in order to take design decisions.

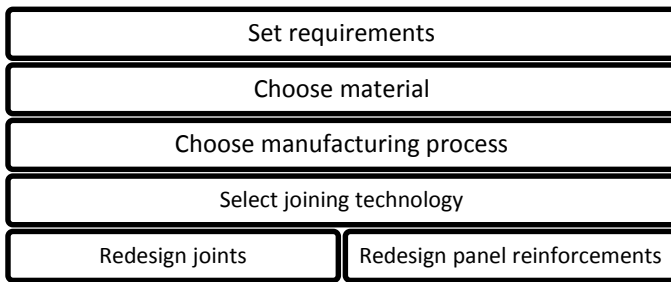


Fig. 7 A detailed view of activities involved in the material substitution project, translated from the process model

## 6. Findings

The authors found that while setting up requirements proved to be a challenge, the main issue with the design engineering-based approach came when trying to evaluate joining technologies (the activity “select joining technology” in Fig. 7, corresponding to “concept evaluation” and “concept selection” in Fig. 6). With the existing information, no decision on joining technology could be taken without it being arbitrary, due to a lack of data for comparing options. The authors estimate the activity of redesigning reinforcements to be a solvable and straightforward activity if the material and the joining technology for the body to the side were decided, but this has not been tested.

## 7. Discussion

While the authors approached the material substitution project in a manner different from the benchmarked earlier projects, by both including product and production development, the result was similar: the project resulted in a heavily compromised solution (in this case a paused project). Several projects [12, 11, 30] presents their findings that piece-by-piece substitution projects become compromised and skew the results, in favor of current solutions.

One contributing factor to the issues with setting up requirements is the challenge of extracting requirements for the body side from the requirements affecting the whole BIW. If the project was done as a major redesign project, redistribution of loads between components would be easier than as currently, when the project was set up as a substitution project.

In other substitution projects focusing on material substitution, initiated at Linköping University as cases for product developing student projects, arbitrary design decisions have been observed in the development process. In one project, the team followed a simple linear project model, and in another the team followed a two-iterations linear project model. Comparing these two observations with the case explored here, this project follows the same structure, sooner or later an arbitrary decision must be taken.

A possible solution for these arbitrary decisions could be to take a depth-first analysis instead of a breadth-first ditto, but

when evaluating such a project towards Ulrich and Eppingers [15] criteria for a successful product development project, it would be hard to argue for a low development cost. The current way of arbitrary decisions could on the other hand be argued to fail the criteria of development capability since the developers would not have gained knowledge that increases neither product quality or cost, nor development time or cost [15].

## 8. Conclusions and future work

The findings from this case project further emphasized the challenges of introducing lightweight materials in automotive BIWs via part-by-part substitution projects. As of now, it appears like breadth-first analysis substitution projects end up with arbitrary design decisions somewhere within the project. In this project, this arbitrary decision occurred when the joining technology was supposed to be evaluated. While this could be mediated by switching to a depth-first analysis approach, this is connected to higher development cost and is not acknowledged as good design engineering practice at the moment.

For future work, the authors would like to continue with the research on how to introduce new materials in BIWs, and evaluate what factors that affect whether substitution projects can be fruitful or not. The current work has pointed towards a threshold for differences in material properties affecting the success of substitution projects, and the authors would like to identify these threshold properties.

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