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# Conceptual design of suspensions with integrated electric motors on the basis of DSM

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**Abstract:** To successfully realize the design by combing two systems multifaceted issues need to be considered. The potential functional conflicts between the existing systems are the major unfavorable factors limiting the design. In order to better complete the design, the physical relationships of the design elements in the systems should be figured out. This paper applies the Design Structure Matrix (DSM) to design suspensions combined with electric driving unit for electric vehicles (EVs) to support the engineering functional integration process. In the process, the mutual relationships of design parameters in the systems are described by means of design structure matrices. Two engineering cases are illustrated in this paper to show this process.

*Keywords: product design, electric vehicles, suspension, engineering functional integration*

## 1 Introduction

Automobile manufacturers developing electric vehicles currently tend to convert existing conventional internal combustion engine powered vehicles into designs for electrically driven automobiles. Changing of boundary conditions and requirements associated with electric mobility are taken into consideration. Lightweight design and creating space through new package variation are new important design requirements of suspensions for electric car development.

Especially regarding automobile applications where other lightweight design methods like the usage of new materials or form optimization are already deeply exploited, further weight saving can be found by the integration of functions (Ziebart 2012).

Consequences of lightweight design by component function integration are that the resulting products are smaller, lighter and cost-efficient (Ziebart 2012) for example sandwich structures for automotive application (Kopp et al., 2009) and a metallic casting A-pillar in the front body structure (Beeh et al., 2013). A functional integration process for mechanical design refers to the realization of the functions of two systems by only one system. The design of functional integration is a very challenging task in engineering, as the designer must creatively and carefully select the design parameters (DPs) in the systems to combine and systematically evaluate the compatibility of the combined design. The physical status change of the selected DPs may affect other associated DPs, because after combination they are associated with each other; these associations may cause an unexpected performance of the design. Without design knowledge and experience, it is hard to enable the new concept with the integrated functions without appearing undesired properties.

Electric lightweight suspensions integrating drive units into the chassis (Pautzke 2010) have the advantage of reducing unsprung mass (Friedrich 2013), creating space through new packaging variations (Kriescher and Brückmann 2012) and incorporating individual wheel drives (Höfer et al., 2015).

DSM has more advantages for analyzing the interaction of existing products (Tang et al., 2008). In the automotive environment product based DSM have found various applications. DSM that helps to integrate two independent products has not yet been part of the research publications and will be outlined in the following work.

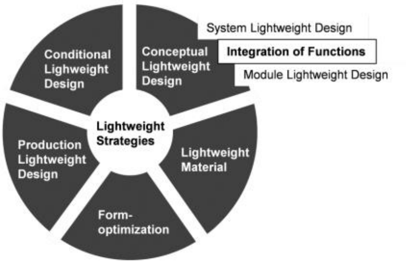



Figure 1: Overview of lightweight design strategies (Henning and Moeller 2011)

## 2 Fundamental of design structure matrix

A product DSM is a square matrix whose rows and columns are identically labeled with the product components, and whose off-diagonal cells indicate component interfaces (Sosa et al., 2007). The cells along the diagonal of the matrix represent the system elements. A cell can have inputs entering it and outputs leaving it (see Figure 2) representing a flow of information (see Figure 3). Off-diagonal on the lower side represents information flow that feeds the following elements; the upper side indicates that the element feeds something back upstream (Helo, 2006). The level and strength of dependency between components can be expressed by the DSM. It is able to provide critical information such as performance metrics and failure rates. This information helps project managers to identify components of importance that will require particular attention in the design process.

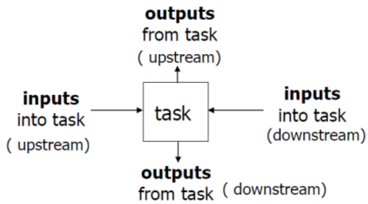



Figure 2: Inputs and Outputs of a DSM (Weck, 2012)

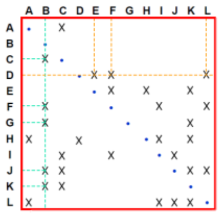



Figure 3: Flow of Information of a DSM (Weck, 2012)

Traditionally the researchers construct the DSM by interviewing the relevant technology engineers and documentations when the most important decisions about the system and the design are made (Dong und Whitney 2001).

# 3 Application

This paper applies DSM methods to product functional integration to realize lightweight design. The interaction among the design parameters can be studied by the DSM, which is proper tool to visualize the product architecture and relationships of the DPs. This provides the engineers another way to analyze the new concept and improves the success rate of the new concept development.

At first the independent systems should be decomposed until the design level with the common combined components. Then, the matrix flow should be investigated by the way of literature review, expert consulting, team talking or some advanced design models, with which the design hierarchy of each system is written as the matrix equation. After that, the matrices of the independent systems are arranged in one matrix equation which represents the combined system. The combined components appear in a unified matrix. Unknown flows appear on the off diagonal of the new matrix, which represent the cross effects of one system on the other system. The unknown element should be defined in order to probe the influence of the combination on the system. The DSM of the new combined concept can be derived from the DM. The DSM of the new concept improves the understanding of the intern relationships and compatibility among the design parameters. It helps to identify the important parameters, guide the engineers to pay more attention on these parameters. In the further development, engineers can take advantage of the DM and DSM to plan the engineering design.

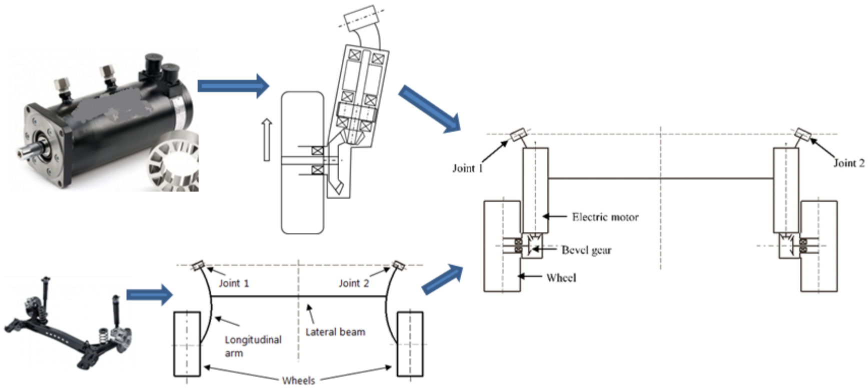



Figure 4: Plan view of the whole suspension concept

## 3.1 Concept design of suspension combining electric motors

The optimization of power-to-mass and torque-to-mass ratios of motors for EVs makes it possible to integrate the electric motors into suspensions. A large number of these suspensions appear in patents, papers and products, for examples the Active Wheel from Michelin (Vijayenthiran 2008), the VDO eCorner from Siemens (Sterbak 2007). The development integrating electric motors and suspension depends on designer knowledge and experience, so it is hard to enable the new concept to perform the integrated functions as expectation without appearing undesired properties. Based on the DSM, the engineering process can be carried out with awareness of the relationship of the design parameters. The concept idea under background of this project is depicted in Figure 4. The electric motor in this picture is designed to integrate to the longitudinal arm of the twist beam suspension.

$DP_m$:

- $DP_{m1}$: Rotor and stator
- $DP_{m2}$: Motor case
- $DP_{m3}$: Output shaft assembly

$DP_s$:

- $DP_{s1}$: Joints
- $DP_{s2}$: Arms and links
- $DP_{s3}$: Spring rate
- $DP_{s4}$: Damper coefficient
- $DP_{s5}$: Sprung mass
- $DP_{s6}$: Bushing
- $DP_{s7}$: Wheel alignment
- $DP_{s8}$: Wheel mass (interaction force of wheel and road)
- $DP_{s9}$: Anti-roll bar

| | $DP_{m1}$ | $DP_{m2}$ | $DP_{m3}$ |
|---|---|---|---|
| $DP_{m1}$ | 2 | | |
| $DP_{m2}$ | 1 | 2 | 1 |
| $DP_{m3}$ | 1 | | 2 |

| | $DP_{s1}$ | $DP_{s2}$ | $DP_{s5}$ | $DP_{s4}$ | $DP_{s8}$ | $DP_{s3}$ | $DP_{s9}$ | $DP_{s7}$ | $DP_{s6}$ |
|---|---|---|---|---|---|---|---|---|---|
| $DP_{s1}$ | 2 | | | | | | | | |
| $DP_{s2}$ | 1 | 2 | | | | | | | |
| $DP_{s5}$ | 0.5 | 0.5 | 2 | 2 | | 2 | 0.5 | | |
| $DP_{s4}$ | | | 2 | 2 | 2 | 2 | | | |
| $DP_{s8}$ | 0.5 | 0.5 | | 2 | 2 | 2 | | | |
| $DP_{s3}$ | 1 | | 2 | 2 | 2 | 2 | 2 | | |
| $DP_{s9}$ | 1 | | | 1 | | 2 | 2 | | |
| $DP_{s7}$ | 1 | | 1 | | | | | 2 | 2 |
| $DP_{s6}$ | | | | | | | | 2 | 2 |

Figure 5: decomposition and the interactions of the design elements

The motor and the twist beam axle are decomposed and the interactions of the design elements are expressed by the matrix in the figure 5. In each row the design parameters playing a major role are chosen as the output variables which are represented by “2”; the elements with strong interaction but not adjustable are marked by “1”; the elements with normal interaction and not adjustable are marked by “0.5”. According to the principles constructing DSM, the off-diagonal cells in the lower triangular matrix represent the forward information which affects the later element; the off-diagonal cells in the upper triangular matrix represent the feedback information i.e. the iteration.

The design elements of the two systems are arranged in one DSM, in which the design element $\mathrm{DP_{m2}}$ and $\mathrm{DP_{s2}}$ are combined to one element $\mathrm{DP_{ms2}}$. The DSM is constructed and clustered according to the primary acting DPs. According to the engineering competence und facility of the research and development section the form of the result may be less different. This concept is modularized into four parts: joints, electric motors, vertical dynamics and driving stability which are distinguished by the use of four colors (see Figure 6). The interaction between the four parts is show in the DSM. From the interaction we can know that $DP_{s5}$, $DP_{s4}$, $DP_{s8}$, $DP_{s3}$ and $DP_{s9}$ must be paid more attention in the concept development, because they contained more primarily acting forward or feedback information for other DPs. From the perspective of modularity, the $DP_{s3}$ is an important DP for both the vertical dynamics and driving stability. Therefore, it must be considered in the development of these two modules. The matrix tools allow the engineers to better understand the functional integration process and the further development process.

| | $\mathrm{DP_{s1}}$ | $\mathrm{DP_{m1}}$ | $\mathrm{DP_{ms2}}$ | $\mathrm{DP_{m3}}$ | $\mathrm{DP_{s5}}$ | $\mathrm{DP_{s4}}$ | $\mathrm{DP_{s8}}$ | $\mathrm{DP_{s3}}$ | $\mathrm{DP_{s9}}$ | $\mathrm{DP_{s7}}$ | $\mathrm{DP_{s6}}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\mathrm{DP_{s1}}$ | 2 | | | | | | | | | | |
| $\mathrm{DP_{m1}}$ | | 2 | | | | | | | | | |
| $\mathrm{DP_{ms2}}$ | 1 | 1 | 2 | 1 | | | | | | | |
| $\mathrm{DP_{m3}}$ | | 1 | | 2 | | | | | | | |
| $\mathrm{DP_{s5}}$ | 0.5 | 1 | 0.5 | 1 | 2 | 2 | | 2 | 0.5 | | |
| $\mathrm{DP_{s4}}$ | | 1 | | 1 | 2 | 2 | 2 | 2 | | | |
| $\mathrm{DP_{s8}}$ | 0.5 | 1 | 0.5 | 1 | | 2 | 2 | 2 | | | |
| $\mathrm{DP_{s3}}$ | 1 | | | | 2 | 2 | 2 | 2 | 2 | | |
| $\mathrm{DP_{s9}}$ | 1 | | | | | 1 | | 2 | 2 | | |
| $\mathrm{DP_{s7}}$ | 1 | 0.5 | | 0.5 | 1 | | | | | 2 | 2 |
| $\mathrm{DP_{s6}}$ | | 1 | | 1 | | | | | | 2 | 2 |

Figure 6: The DSM of the concept suspension

Taking the advantage of DSM, the main DPs have been determined using engineering methods. Among these parameters, the joints are the most basic element, which should be defined at first. The primary parameters of the electric motor ($\mathrm{DP_{m1}}$: Rotor and stator) are calculated according to the vehicle power requirements; $\mathrm{DP_{m3}}$ are designed according to the transmission requirements with the condition of $\mathrm{DP_{m1}}$ (see Figure 7(a)). Topological structure for the concept suspension is applied under consideration of the design elements of the electric motors (see Figure 7(b)). The result of the structure optimization provides a feasible topology for the concept development, which satisfies not only the mechanical but also the K&C requirements. The design parameters in the last group are strongly related to the vertical suspension dynamics. An analytical model for rear-axle vehicle dynamics and a double lane model of road irregularities are developed (see Figure 7(c)). The parameters of the spring and damper are investigated by the analytical model of the ride dynamics.

(a)

$F_{Req} = F_T = F_R + F_A + F_G + F_I$

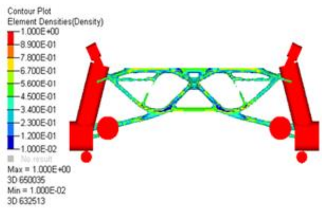
Requirements:

Highest speed: 150 km/h

Acceleration:12s/(0-100 km/h)


| | $DP_{s1}$ | $DP_{m1}$ | $DP_{ms2}$ | $DP_{m3}$ | $DP_{s5}$ | $DP_{s4}$ | $DP_{s8}$ | $DP_{s3}$ | $DP_{s9}$ | $DP_{s7}$ | $DP_{s6}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $DP_{s1}$ | 2 | | | | | | | | | | |
| $DP_{m1}$ | | 2 | | | | | | | | | |
| $DP_{ms2}$ | 1 | 1 | 2 | 1 | | | | | | | |
| $DP_{m3}$ | | 1 | | 2 | | | | | | | |
| $DP_{s5}$ | 0.5 | 1 | 0.5 | 1 | 2 | 2 | | 2 | 0.5 | | |
| $DP_{s4}$ | | 1 | | 1 | 2 | 2 | 2 | 2 | | | |
| $DP_{s8}$ | 0.5 | 1 | 0.5 | 1 | | 2 | 2 | 2 | | | |
| $DP_{s3}$ | 1 | | | | 2 | 2 | 2 | 2 | 2 | | |
| $DP_{s9}$ | 1 | | | | | 1 | | 2 | 2 | | |
| $DP_{s7}$ | 1 | 0.5 | | 0.5 | 1 | | | | | 2 | 2 |
| $DP_{s6}$ | | 1 | | 1 | | | | | | 2 | 2 |

(b) Structure optimization considering K&C performance




(c)

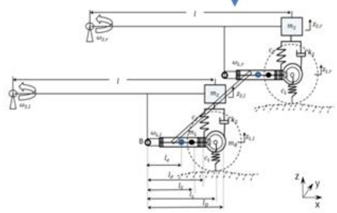


Figure 7: Engineering process based on the design matrix

According to this process the suspension concept has been further developed into the detail design phase (see Figure 8). This suspension is mounted to the vehicle body through the bushing bearings, the springs and dampers. The lightweight linkage connects the left and right wheels and supports the lateral force on the wheels, and meanwhile it functions as an anti-roll bar with a certain torsional stiffness. The electric motors produce the drive force, which is transferred to the wheels through the gears for the whole vehicle. The reaction force on the wheels is transferred to the vehicle body through the wheel hub, the case of the gearbox, the case of the motor and the bushing bearing or the spring and damper.

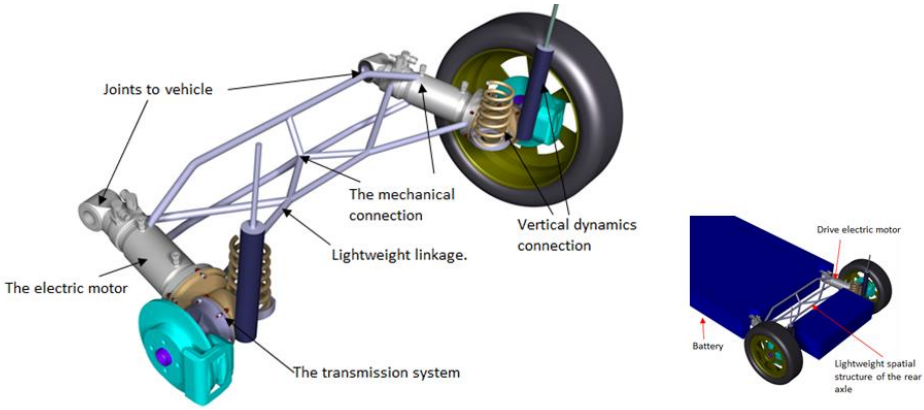



Figure 8: Plan view of the whole suspension concept

### 3.2 Prototype design of suspension with electric motors close to wheel hub

Another application of the DSM is in the development of the suspension with electric motor close to wheel rub. The construction of the concept is shown in figure 9. The concept has the following characteristic features (Höfer, et al. 2015) (Höfer, et al. 2016): The conventional wheel bearing in the center of the wheel is replaced by bearing elements, (1). This connects the rotating and stationary parts of the chassis. Each bearing element is fitted with six spherical roller bearings, (2), which execute rolling motion inside the rim. The space available within the wheel bearings is used to position two guide elements, (3). Vertical force absorption is implemented using two coil springs, (4), integrated into the wheel. The shock absorbers attached to the lower wheel bearing element, (6), serve as the suspension's upper impact point. A monotube shock absorber ((7), partly hidden) is used. The lateral forces induced in the wheel contact patch are passed on to the two wheel bearings via two lateral guide rails, (8). The bearing seal (9) is a labyrinth seal produced by additive manufacturing.

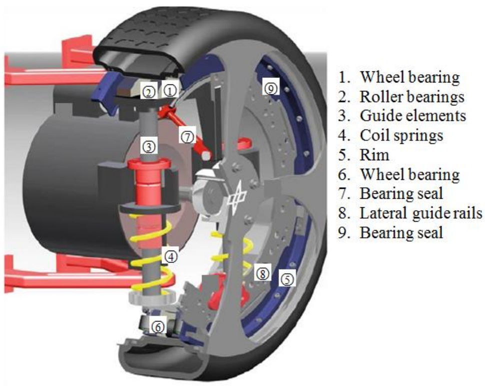



Figure 9: Lightweight suspension construction

The DSM of this suspension concept is show in figure 10, which is the first level DSM structure. It can be analyzed that the wheel bearings and the guide elements have the most interactions with other design elements. The rim, lateral guide rails and bearing seal are influenced by electric motors, guide elements and bearings.

| | $DP_{m1}$ | $DP_{s1}$ | $DP_{s6}$ | $DP_{s2}$ | $DP_{s3}$ | $DP_{s5}$ | $DP_{s8}$ | $DP_{s9}$ | $DP_{s4}$ | $DP_{s7}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $DP_{m1}$ | 2 | 1 | | | | | | | | |
| $DP_{s1}$ | | 2 | | 1 | | | 0.5 | | | |
| $DP_{s6}$ | | | 2 | 1 | | | 0.5 | | | |
| $DP_{s2}$ | | 1 | 1 | 2 | 2 | | | | | |
| $DP_{s3}$ | 0.5 | 1 | 1 | 2 | 2 | 2 | 2 | | | |
| $DP_{s5}$ | | 1 | 0.5 | | 2 | 2 | 2 | 2 | | |
| $DP_{s8}$ | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 2 | 2 | 2 | | |
| $DP_{s9}$ | 1 | | | | 1 | 2 | 2 | 2 | | |
| $DP_{s4}$ | 0.5 | 1 | | 1 | 0.5 | | | | 2 | 2 |
| $DP_{s7}$ | 0.5 | 1 | | 1 | 0.5 | | | | 2 | 2 |

Figure 10: General DSM of the lightweight suspension

The design elements and the DSM are further developed. The development process of the physical concept can be seen in the figure 11. The rim and lateral guide rails are designed and validated by using FEM; the electric motor, springs and dampers are defined in the multibody dynamics and they are further optimized on the basis of this multibody simulation. According to the results of the design elements, a prototype suspension is built. The design parameters and the relationship among them will be further validated and developed.

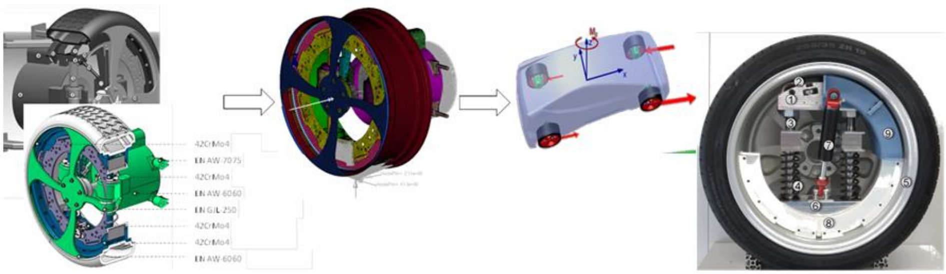



Figure 11: Design (CAD) and simulation (FEM and MBS) of the lightweight suspension

## 4. Conclusion

This paper has devoted to apply the DSM in the concept development which aims to integrate the function of two systems on the purpose of structure lightweight. The design process is expressed by matrix equations on the basis of DSM. The DSM helps the designer to understand the relationship between the system functions and parameters and the interaction among the design parameters in the design process. Two case applications are illustrated in this paper. The matrix among DPs benefits the designer to evaluate and compare the concepts, while the DSM helps the engineer identify the important DPs and assist the engineering process. Based on the DSM, the relationship between the systems to be combined and the relationship among the DPs are shown in the design matrix. The visible relationship enables the functional integration design be managed in a more effective and logical manner than the traditional concept–test design way.

The principle of this approach can serve as a theoretical foundation for the future design research. For example, a database based on the design matrix for the automotive components can be built. The possibility combining the components to achieve lightweight design can be studied by this approach, which is a time-saving and cost-saving process.

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