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Computing solution spaces for gear box design

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Abstract

The design of gear boxes is a complex challenge characterized by conflicting requirements and seemingly circular dependencies. Existing tools support engineers but focus on a single predefined design, often leading to costly iterative processes and non-optimal solutions. Solution Space Engineering (SSE) alleviates this by generating multiple designs represented by solution spaces. For this, a particular model structure is needed, and thus restructuring existing models, e.g., from industry standards. The application of solution spaces to a two-stage gear box is presented.

Keywords: design tools, design process, product development, gear box design

1. Introduction

For successful product development, it is important to satisfy customer demand (market-specific goals or external view) while ensuring a profitable performance on the producer side (company-specific goals or internal view) (Luft, 2022). Especially in the offer phase where little is known about the final product additional costs can arise. Knowledge about already developed similar products and tools to manage this can be useful. Due to the importance of the developer's decisions for the success of the product, it is essential to support developers with the increasingly complex challenges.

Solution Space Engineering (SSE) can be used for mastering complexity and was introduced by Zimmermann and Hoessle (2013). SSE suggests to model all quantitative dependencies between the quantities of interest (QoI) which can be compared to the value of the requirements and the design variables (DV) which can be adjusted by an engineer. Good designs, that fulfil the requirements can be generated and e.g., box-shaped solution spaces within the area of good designs can be derived to decouple DVs.

The computed solution space is useful for detailed design. Subsequent optimizations like cost optimization and product family design can be performed. Rötzer et al. (2020b) computed solution spaces for different product variants, identified the overlaps between the solution spaces and derived the cost-optimal product family. In case of different suppliers, requirements from the system level can be broken down to enable distributed development, e.g., of the gear wheels, shafts, and housing. This paper presents the first step in generating solution spaces for gear boxes. Cost optimization and product family design are not included.

The overall objective of this work is to compute solution spaces for the design of two-stage gear boxes. This leads to the following research questions:

- Which types of models need to be considered in gear design, and how do they have to be modified for a more effective and efficient gear box development?

- Is it necessary to adapt models depending on the requirement type of different design phases (e.g. offer phase, order processing)?
- Which advantages and disadvantages does the use of solution spaces have in comparison to the classical approach for the design of gear boxes?

The aim of this paper is a first application of solution spaces to the design of gear boxes and does not present a complete gear box design. Therefore, several simplifications were made, e.g., lubrication effects, requirements on the noise characteristics and requirements on the efficiency were neglected. Further assumptions were made, e.g., with choosing hardened steel as material, the profile shift coefficient was assumed as 0, an application factor of $K_A = 1$ and gear tolerance class of 6 was chosen.

2. State of the art

2.1. Gear box design

Designing a gear box requires the specification of numerous parameters. On a macroscopic level it is a suitable powertrain topology that engineers elaborate to be able to meet the specified requirements. Commonly used are single or suitably combined cylindrical, bevel, planetary or worm gear stages. The total gear ratio must be split among the gear stages. Several approaches exist for defining the required number of stages and their respective gear ratios. These models focus on different optimization goals (e.g., maximum use of strength, minimum volume or mass, minimum moment of inertia) and vary in the level of considered details (Niemann and Winter, 2003; Römhild, 1993; Kanarachos et al., 1987; Moeser, 1982; Parlow, 2016; Parlow and Otto, 2016; Gärtner and Herrwig, 1974; Savsani et al., 2010; Fürst et al., 2022). State-of-the-art methods for semi-automated gearbox design and synthesis include optimization strategies, such as simulated annealing, genetic algorithms and burst algorithms, knowledge-based engineering, constraint programming and (graph) grammars (Sendlbeck, 2023).

Based on the given required gear ratio, an appropriate macro geometry of the individual gears must be identified, resulting in a consistent set of the main gear parameters: centre distance a, gear widths b, normal module m_n, number of teeth z, profile shift coefficients x, addendum h_a and dedendum h_f.

This step is commonly referred to as gear synthesis (Parlow, 2016). Two main approaches have been established and are similar in one essential aspect: A sufficient dimensioning to resist pitting damage and tooth root fracture.

The first approach takes already established gear boxes in a similar application into account. Two parameters are derived from these gear boxes: the K*-factor as indicator for flank load carrying capacity and the U-factor as a characteristic for tooth root bending strength. With these parameters, the pinions reference diameter d and the number of teeth z can be derived. (Niemann and Winter, 2003)

The second approach makes use of standardized methods for the evaluation of the load carrying capacity, e.g. ISO 6336 (ISO 6336:2006-09), ANSI/AGMA 2001-D04 (AGMA 2001-D4:2004-12). These systems of formulae require gear geometry and loading conditions, among other inputs, e.g., the properties of the shafts, bearings, housing and lubrication. Proper application of such frameworks results in safety factors against typical gear failure modes. By partly inverting the calculation process and starting with predefined safety factors against pitting and tooth root fracture as well as default values for load factors, it is possible to derive a working set of gear geometry parameters. The reference diameter d of the pinion results from the equations related to contact stresses. The normal module m_n originates from formulae in association with tooth root stresses. Due to the complexity of or respectively the low dependency on the macro geometry, the calculation methods for efficiency and dynamics, as well as for other types of damage such as micropitting, scuffing and wear, are used to validate a design, but are usually not referred to for the explicit design process of the macro geometry. (Parlow, 2016; Parlow and Otto, 2016)

In both of the aforementioned concepts, the remaining parameters of the macro geometry are then computed by utilizing a target ratio of width-to-pitch diameter b/d_t, a transverse contact ratio ε_α and an overlap ratio ε_β. The safety factors determined in a subsequent standard calculation are usually close to the specified target values. There are computer-based tools that provide all or part of this functionality.

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Research software such as GAP ("Getriebeauslegungsprogramm") (Fürst and Otto, 2023) assists engineers in designing the gear boxes and STplus (Rothemund and Otto, 2023) does the standard calculation of the geometries. Commercially available software includes KISSsoft (KISSsoft AG, 2023a)/KISSsys (KISSsoft AG, 2023b), MASTA (Smart Manufacturing Technology Ltd.), FVA-Workbench (FVA Software & Service GmbH., 2023), and program systems from MDESIGN (MDESIGN Vertriebs GmbH., 2023) and Romax (Romax Technology Limited., 2023).
REXS and ECLASS offer data standards for gear boxes for the exchange of gear box models (ECLASS e.V; FVA GmbH, 2017).
Almost every specific software suite on gear design has been developed for the purpose of calculating an already defined design. The algorithms are perfectly capable of evaluating load capacity (ISO 6336:2006-09), noise excitation (Höhn et al., 2011; Kohn et al., 2017) and efficiency (ISO/TR 14179-1:2001-07; ISO/TR 14179-2:2001-08) of a gear set. But all approaches require very detailed data which usually is not available during design and probably not clearly known to the engineer during concept phase. So, most software suites do not lend themselves to a straightforward design process (Parlow et al., 2016).

2.2. Solution space engineering

To integrate the relevant data and information, already used in conventional programs mentioned in chapter 2.1, into a straightforward design process, solution spaces can be used. Detailed information, e.g., like characteristic curves for the form factor, has to be included and existing models need to be rearranged to suit the framework of SSE. Usually, a complex system does not only consist of a single gear box. Other components like shafts, housing, motor, and other components also need to be designed or given boundary conditions need to be considered when the parts are already designed. To design a gear box, which is normally a sub-system of a more complex system, e.g., an electric railcar, solution spaces can be used.
To handle complexity in product development various product development models and processes have been developed. Commonly used is the V-model from VDI2206 that translates customer requirements of the system into specific requirements of different disciplines (VDI/VDE 2206, 2021). It helps to manage complexity by developing components from different disciplines separately. After developing the concept of the disciplines, the system is merged by combining the developed components and verifying the correct development. This procedure leads to time-consuming and cost-intensive iterations, which should be avoided as far as possible during development (Luft et al., 2013). The result often leads to a single solution. As a simple example, the design of a one-mass oscillator in Figure 1 is shown. A traditional design process leads to a single solution (Figure 1 (c)) for a mass (m) and stiffness (c) value. For distributed design teams it can be hard to reach a specific value for their design. To overcome this limitation, solution space engineering is introduced by Zimmermann and Hoessle (2013). Requirements on the system level are broken down to requirements on component or detailed level, depending on the aim of the design task and which design variables need to be determined. A box-shaped solution space can be computed, that includes only good designs while decoupling design variables. In Figure 1 (d) the result for a simple system using SSE can be observed. The green area visualises all good designs, that fulfil the requirements on system level. The box shows the designs that can be used when the design variable mass and stiffness are decoupled. It helps e.g., when one engineer designs the mass related part of the system and another one the stiffness related part to make them work independently.

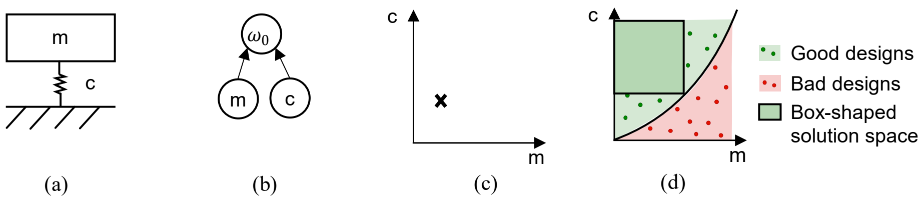

Figure 1. (a) Model of a one-mass oscillator, (b) ADG (c) point-based design and (d) interval-based design

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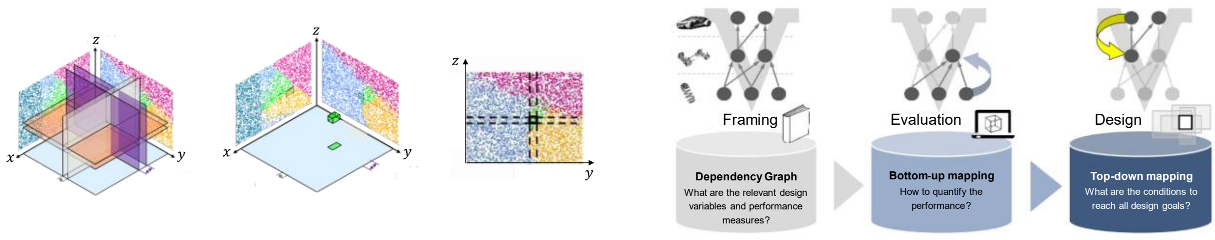
In addition to this simple example, SSE can be used for high-dimensional problems. Successful real-world examples of this methodology are presented, e.g., in the context of automotive crash design (Zimmermann and Hoessle, 2013), design of vibratory rammer (Xu et al., 2023), product family design (Rötzer et al., 2020b) and robotics (Sathuluri et al., 2023). Instead of computing solution spaces using specialized software, e.g., by Zimmermann and Hoessle (2013) an interactive tool to construct solution spaces manually is applied in this paper. To construct a box-shaped solution space, proceed as follows: Define candidate intervals for each design variable. Then project slabs of the design space with thickness corresponding to the specified interval size onto 2D planes for each pair of design variables, see Figure 2 (c). If the intersection of the slabs contains bad designs, adjust the intervals appropriately. If it contains only good designs, it is a box-shaped solution space (Figure 2 (b)).



(a) (b) (c) (d)

Figure 2. (a) Slabs of the design space resulting in (b) a box-shaped solution space and (c) a 2D projection (Zimmermann and Weck, 2023) (d) Three steps of SSE (Zimmermann et al., 2017)

Three steps – framing, evaluation and design – are proposed by Zimmermann et al. (2017), shown in Figure 2 (d). In the first step, attribute dependency graphs (ADG) are used to visualize the dependencies. On the lowest level, design variables (DV), which can be influenced by a designer, are located. They influence the quantities of interests (QoI) on the highest level. By using ADGs, circular dependencies are avoided systematically. The values of the QoIs are assessed by the requirements to distinguish between good and bad designs. In the second step a quantitative modelling is carried out. In the third step requirements on the system level are broken down to compute solution spaces with permissible intervals for each design variable.
They can be classified as customer requirements and internal technical requirements (Zimmermann and Weck, 2023). To deal with equality-type requirements Stumpf et al. (2020) introduces different approaches. One approach, “Relaxed Problem Statement,” defines a small allowable range around the nominal values of the equality constraints. However, the resulting solution space is not well suited to decouple the design variables because the maximum solution space is often too small. Another approach is to express a design variable as a function of the other design variables and the quantity of interests with the exact equality constraint. Large systems can be modelled by using sub models for properties (Rötzer et al., 2020a) or time-dependent behavior (Ziegler et al., 2023).

3. Gear box design using solution spaces

To apply solution space engineering to gear box design, a use case of a two-stage gear box in the field of electric railcars is presented. The structure of the gear box is presented, including relevant DVs. For identifying the QoIs, the relevant requirements are shown. Challenges that occurred while applying SSE to the gear box design and possible solutions will be presented. These challenges can also occur in other development processes when SSE is used.

3.1. Structure of the gear box

Figure 3 shows a schematic of a two-stage gear box designed for use in electric railcar applications. The operating principle can be described as follows: The gear box is driven by an electric motor, which transfers power to the pinion shaft (1). The teeth (1a) of the pinion shaft engage with the cylindrical gear (3a), which is both rotatable and axially secured to the intermediate shaft (3). The teeth (3b) of the intermediate shaft mesh with the cylindrical gear (4a), which is rotatable and axially secured to the output shaft (4). Two drive wheels are mounted on both sides of the output shaft (4), also rotatable and

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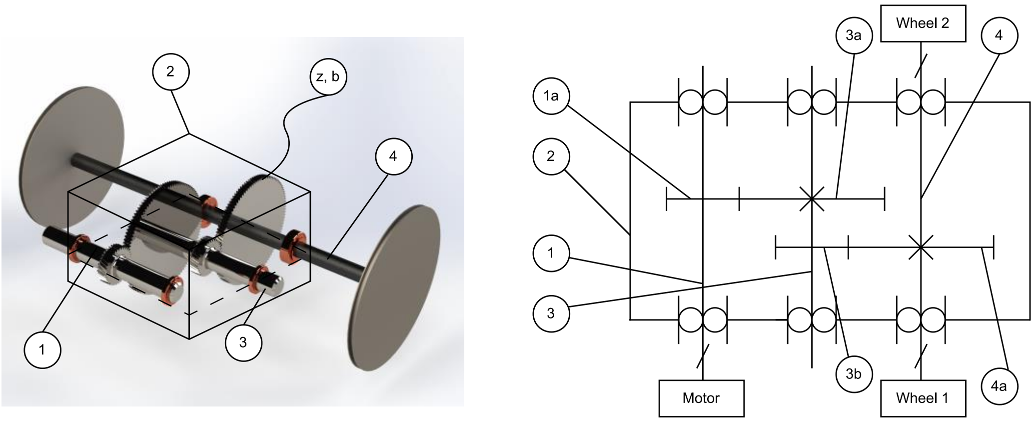
axially secured. All shafts are located in the housing (2). DVs like number of teeth z and face width b can be derived from the structure.



(a) (b)

Figure 3. Two-stage gear box (a) CAD drawing and (b) sectional view

3.2. Requirements on the gear box

QoIs can be derived from requirements on the system level. In the offer phase, a range of requirement values is used to provide flexibility to the manufacturer, shown as case 1. In the order phase, where the manufacturer must fulfil the customer requirements, exact values are presented to the customer, which is shown in case 2. Table 1 outlines the requirements for both cases.

Table 1. Requirements list for two different cases

Requirement type	Quantity of Interest	Description		Value		Unit
				Min.	Max.	
Customer requirements	a_x	Horizontal centre distance	Case 1	400	500	mm
			Case 2	450		
	a_z	Vertical centre distance	Case 1	5	20	mm
			Case 2	10		
	v_{fzg}	Maximum vehicle speed		120	$-$	$\frac{km}{h}$
	s_H	Ground clearance		0.06	$-$	m
Internal requirements	S_F	Safety factor for the pinion/gear for tooth breakage		1.5	$-$	$-$
	C_P	Structural requirement on the pinion/intermediate shaft		1	$-$	$-$
	C_O	Structural requirement on the output shaft		6	8	$-$
	P	Structural requirement on the pinion position		0	0.3	$-$
	σ_{FP}	Permissible nominal tooth root stress		310	525	$\frac{N}{mm^2}$

3.3. Modelling of the gear box in accordance with SSE

The traditional design process of gear boxes shown in Figure 4 (a) is subject to iterations. For SSE, the system model is restructured according to Figure 4 (b). This will avoid iterations. The gear box model is divided into six independent submodules. The traditional module “desired transmission ratio” is not needed anymore. The new modules “Structural calculations”, “tooth bending strength” and “strength of material” are included in the traditional module “tooth profile”. Every sub model consists of a model with QoIs and DVs. With the sub model “Vehicle speed” v_{fzg} is computed, with “Structural calculations” P, C_P and C_O are computed, with “Centre distance” a_x and a_y are computed, with “Tooth

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bending strength" S_F is computed, with "Strength of material" σ_{FP} is computed and with "Ground clearance" s_H is computed.

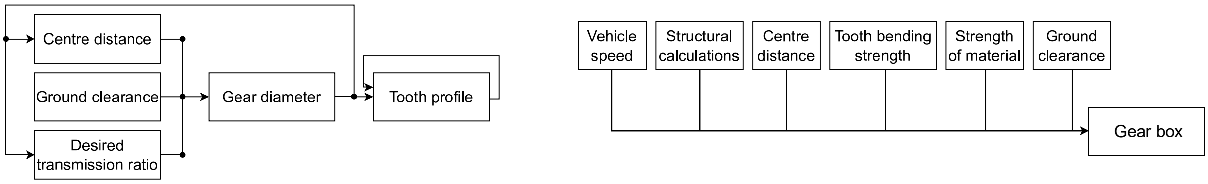

Figure 4. (a) Traditional gear box design process (b) Gear box design process without iterations

As an example, the sub model "vehicle speed" is marked with the dotted line in Figure 5. Merging all the sub models into a system, the ADG represents the dependencies between QoIs and DVs of the whole system, which shows that there are no circular dependencies.

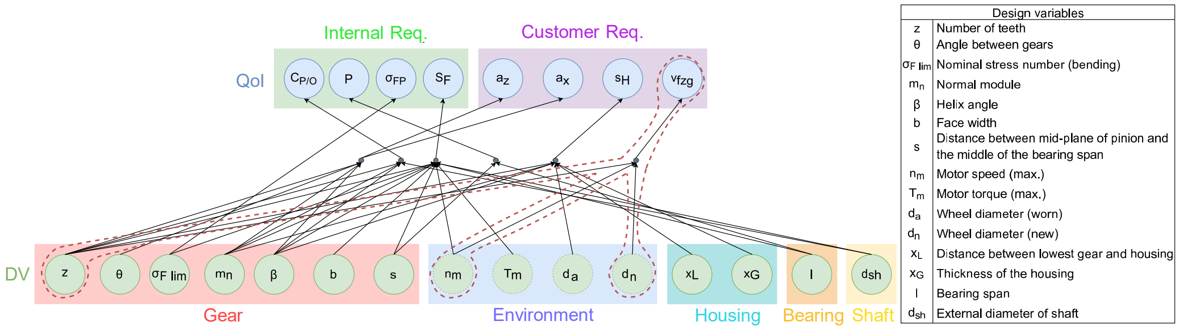

Figure 5. Attribute Dependency Graph (ADG) of gear boxes

Each sub model is an analytical model, derived from existing models and equations, e.g., regulations. By applying SSE, challenges can occur in restructuring the existing models and making them suitable to compute solution spaces.

3.3.1. Restructuring existing models

The right choice of QoIs and DVs is crucial to avoid circular dependencies. In traditional gear box processes, formulas where DVs depend on QoIs are used, i.e., the opposite of what is needed for SSE.

Centre distance. The calculation of the pitch circle diameter is typically performed based on customer-defined centre distances. Since the centre distances are considered QoIs, it is necessary to restructure the model. Therefore, a new design variable θ, which is an angle that influences the centre distances, is introduced. The ADG for the new model is shown in Figure 6.

Vehicle speed. A similar problem exists in the following process, where a desired transmission ratio $i_{desired}$ was computed from the desired vehicle speed v_{fzg} specified by the customer and an actual transmission ratio i_{actual} was found using the number of teeth z, see Figure 6. Since the vehicle speed v_{fzg} is a QoI, the formula must be rewritten to compute v_{fzg}. This abolishes the terms i_{actual} and $i_{desired}$. The transmission ratio i is selected in such a way that it meets all relevant requirements.

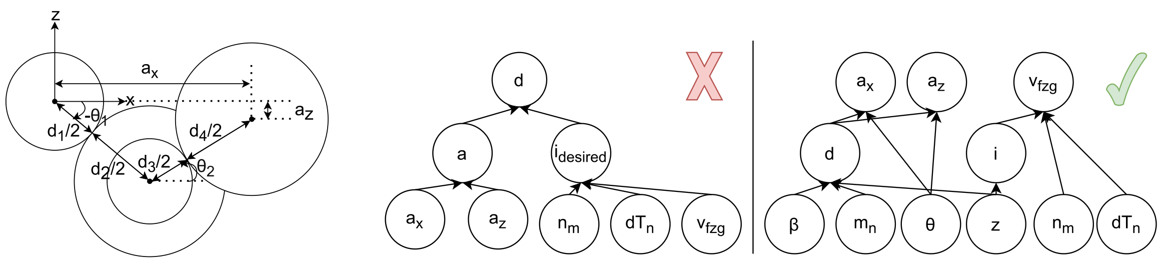

Figure 6. Model of the centre distance (left), traditional (middle) and restructured (right) ADG

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Integrating safety factors. To determine safety factors, extensive calculations with iterations are necessary in the traditional approach, see Figure 7. The model was restructured according to SSE. In this work, only the safety factor for tooth bending strength has been implemented as an example and in a simplified manner, e.g., without considering the pressure angle, tooth root radius and profile shift. Furthermore, simplifying of a factor that varies with materials or working characteristics can be useful. These may not vary if a manufacturer wants to produce only one gear box type and can be written as constants in the calculations. Some factors can be computed analytically, while transcendental equations must be solved to determine intermediate variables. These transcendental equations affect the duration of the calculation of solution spaces. To reduce the computing time and ensure accurate results, reference profiles, implemented graphs and tables can be used.

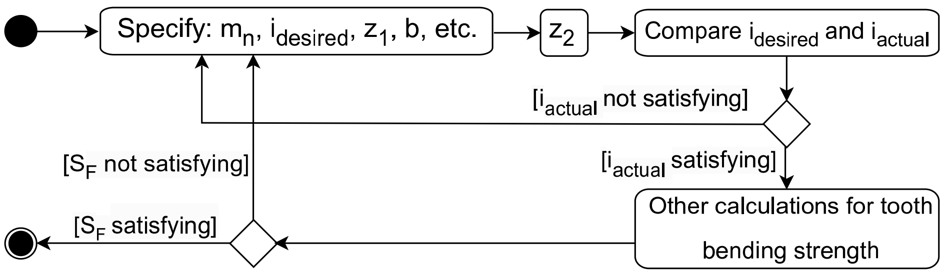

Figure 7. Safety factor calculation in the traditional design process (simplified)

3.3.2. Including feasibility aspects into models

In some cases, it is not sufficient to restructure existing models. When considering discrete values for design variables or point-based requirements, models need to be adapted for SSE. It may also occur that solutions are not practically applicable and requirements on the compatibility are needed.

Modelling with integer discrete values. As the points in the design space are generated through Monte Carlo sampling of rational numbers and are most likely not integers, a rounding function is used. This applies to the number of teeth z. Therefore, a modified rounding function ensures an increase of 1. In case of point-based requirements, the solution space reduces to a line. Consequently, an interval cannot be selected; only a single point can be considered. However, this scenario does not contribute to a meaningful solution space, as its volume is effectively zero. Therefore, the application of rounding functions, while ensuring manufacturability, may lead to impractical solution spaces for a single point solution.

Point-based requirements. The previously mentioned calculation with θ as DV was only applicable for interval-based requirements on the centre distances a_x and a_z caused by the randomly chosen values with Monte Carlo sampling. To extend this methodology to point-based requirements, i.e., $a_x^* = a_{x0}$ the angle θ can be eliminated. To compute the value for the other QoIs, θ becomes a function according to Equation 1. The requirements on a_x^* and a_z^* are point based.

$$\theta = f(m_n, z, \beta, a_z^*, a_x^*) \tag{1}$$

To avoid unrealistic results for θ, a constraint on the design space of θ ($\Omega_{ds,\theta}$) is introduced.

Compatibility. When designing gear boxes, either a shaft with a gearwheel can be used or the tooth profile can be cut into the shaft. In this paper, a combination with gearwheel and shaft is considered. A good design may involve the pitch diameter of the cylindrical gear being smaller than the shaft diameter, but this is not applicable in this case. Therefore, the shaft and the cylindrical gears are proportionally related to obtain a solution where the shaft size does not exceed that of the cylindrical gears. Figure 8 illustrates the effect of structural calculations if the pitch diameter of gear (dashed line) is smaller than the shaft diameter.

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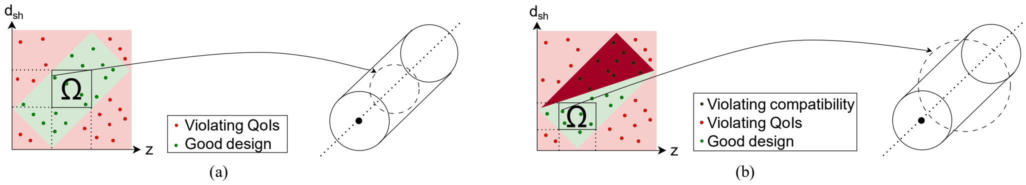

Figure 8. Solution space (a) without and (b) with requirements on the compatibility

4. Results and discussion

Figure 9 and Figure 10 depict the solution spaces of case 1 and case 2, respectively. Conclusions can be made about the possible designs of the gear box and the adaptations mentioned in the method section can be observed and will be explained in the following section.

Design guidelines. For each design variable, a permissible interval can be obtained. E.g., the face width b_1 should be chosen in the interval of [0.08 m, 0.13 m] and b_2 in the interval of [0.08 m, 0.11 m]. In this application the intervals can be useful when, e.g., different train companies apply for the same project and request similar gear boxes with slightly different requirements. In a further step, product family design can be used to find a solution that can be offered to different costumers.

Optimal solutions of box-shaped solution space. In contrast to conventional optimisation methods, solution spaces provide intervals for design variables and not an optimal solution. E.g., z_3 in case 1 can be chosen from the interval [53, 61]. The triangles represent designs that realize the minimum volume of the gears within the box-shaped solution space, thereby saving material and being cost-efficient for material. Conversely, the squares achieve the maximum speed of the vehicle. Depending on the priorities of the manufacturer, a solution can be selected in the solution space according to an optimization target.

Lifetime. Analysing the values for the used wheel diameter d_a the wheel should not be used for $d_a \leq 0.81\, m$. Else, the customer requirement on the ground clearance would be violated. To extend the lifetime of the product, the interval for d_a could be enlarged.

Environment. The manufacturer can easily determine the range of the thickness of the housing x_G and the space between gear and housing x_L without measuring this in the post-manufacturing phase. It provides the possibility to derive requirements on other components than the gear box.

Effects of equality constraints. In case 2, the variable θ is eliminated and can not be observed in the solution space. The orange points show that the requirement on the design space of θ is violated. This is caused because the limit of the design space is exceeded.

Effects of rounding function. Even though there is a solution space for number of teeth z_1 in case 1, there are only 3 designs that are physically feasible. The derived interval for z_1 is [45, 48). As the rounding function was used, only discrete values (45, 46, 47) can be derived.

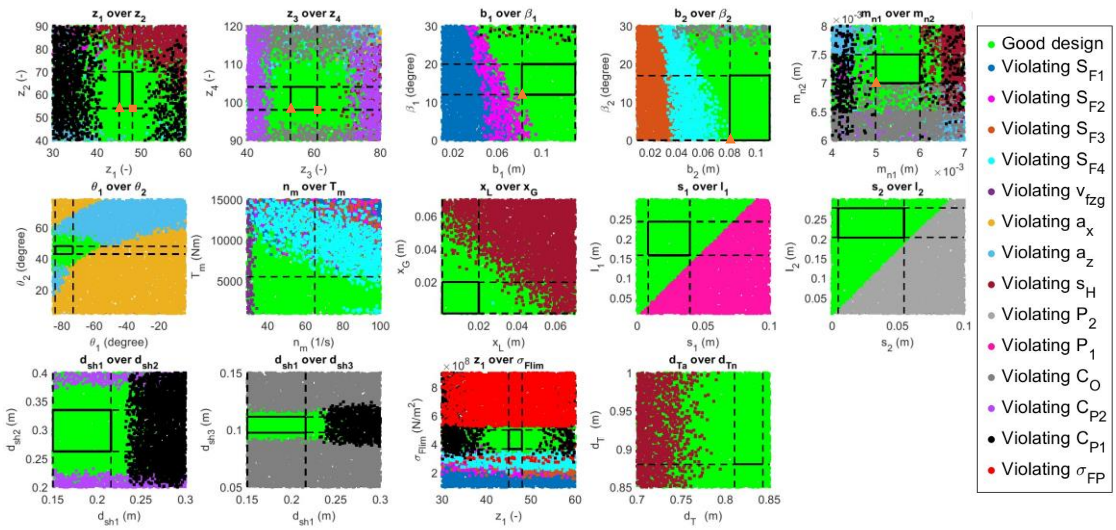

Figure 9. Solution spaces of case 1

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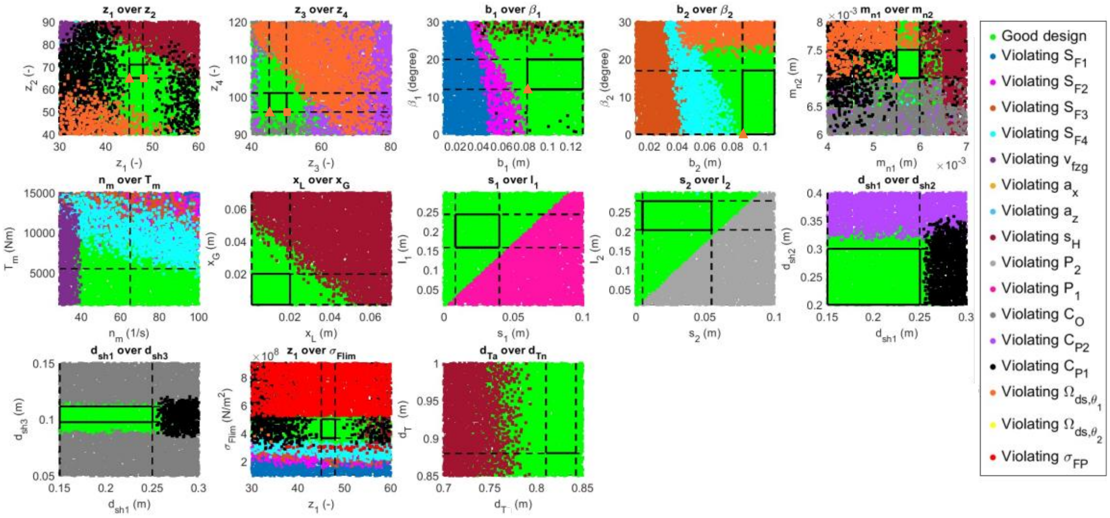

Figure 10. Solution spaces of case 2

5. Conclusion and outlook

Benefits. In this work, solution space engineering was used to break down system level requirements for a two-stage gear to permissible intervals for design variables. Through restructuring existing models, iterations in the design process can be avoided. The design space projection visualises the good regions for multiple dimensions. Intervals for design variables can be easily derived from the plots and enable independent design of components.

Limitations. To compute solution spaces, quantitative models are needed which can lead to a high modelling effort or high computational cost. By using box-shaped solution spaces, parts of the solution space get lost. In general, expertise is necessary to find and evaluate the solution space and it can be quite abstract to explain solution spaces.

Outlook. The application of solution spaces to the design of gear boxes can be extended, particularly in the calculation of safety factors. In further research, despite the 2-stage cylindrical gear, different configurations of cylindrical gears and different types of gear can be subject to design automation with SSE. Therefore, it can be useful to observe the reuse of models systematically.

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