Choosing the right architecture for the next generation of railway vehicles using aerospace methodologies

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Abstract

Environmental concerns and regulations put pressure on the future of diesel power propulsion systems. Due to the expensive infrastructure costs, electric multiple units do not supersede diesel multiple units in the regional railway market comprehensively. Therefore, concepts like the EcoTrain or the Coradia iLint gain ground. They aim to reduce CO2 emission, noise level, and operational costs. Their approaches are highly different. Alstom is offering a brand-new Hydrogen-powered train, whereas the EcoTrain is a hybrid modernization of an existing combustion powered vehicle. An obvious question arises: which train architectures can provide environmental friendlier and future-oriented alternatives to the diesel multiple unit? This paper aims to address this question and shows that aerospace methodologies can successfully be transferred to the railway industry. We discover and define 28 propulsion concepts, develop a model to evaluate and optimize them and make sense of the results to inform the decision-making process.

Keywords: Railway vehicle concepts, hybrid, electrification, system architecture, systems engineering

Thematic area:
Energy and resource efficiency: Innovative vehicle, chassis, and propulsion concepts; Electrification, without overhead wires

1 Introduction

In comparison to other transport vehicles like cars or airplanes, rail systems have a great potential to provide green transportation. Electric multiple units (EMU) enable trains to operate without local CO2 emission and reduced noise level. However, only around 60% of the tracks in Germany are electrified [1]. On the remaining, trains with diesel multiple units (DMU) are currently used. These less frequently operated tracks are usually outside of highly populated areas and hamper the otherwise green image of the railway industry. The electrification of them is at a slow pace due to the often-claimed difficult cost-benefit relationships. We have compared the EMU with the DMU system. In doing so, we have set the sum of the investment and maintenance cost of both systems equal. Then, a minimum required timed-sequence can be obtained. The investment cost per km for overhead wires is around 1 M€ according to two projects, the electrification of Lindau-Ulm [2] and Lindau-Geltendorf [3]. The cost estimations of Baumgartner [4] support this assumption. With a depreciation time of 40 years and a yearly maintenance cost of 2 % of the investment cost, the infrastructure cost for the catenary sums to 45,000 €/km/a. We assume that DMU and EMU have similar maintenance costs. The DMU needs more frequent inspections, whereas the electronic components of the EMU have to be exchanged more often [4]. These contributions offset each other. The variable operational costs differ mainly in the energy cost. We found them to be 1.16 €/km for the DMU and 0.34 €/km for the EMU [5-8]. With equation (1) there must be 54,905 trains on the electrified track in order to break even with the cost of the DMU.

$$\begin{gathered} c_{Energy-DMU} = c_{Energy-EMU} + \frac{c_{Catenary}}{n_{trains}} \\ \rightarrow n_{trains} = \frac{c_{Catenary}}{c_{Energy-DMU} - c_{Energy-EMU}} = 54{,}905\ \frac{trains}{year} \end{gathered} \tag{1}$$

With 16 operational hours per day, the number of trains per year can be translated into a timed-sequence of around 6.4 min. This means that for timed-sequences below this value, it is economically profitable to invest in the electrification and use EMUs instead of DMUs. In comparison, the suburban main line in Munich has a timed-sequence of around 2 min with the outer tracks are in the area of 10 min [9]. The scope of this paper is to address regional tracks which have even higher timed-sequences. In this case, the electrification is economically hardly justifiable as shown by the previous assessment.

Therefore, regional railcar concepts with lower infrastructure cost like the EcoTrain or the Coradia iLint gain ground. They aim to reduce CO2 emission, noise level, and operational costs. Their approaches are highly different. Alstom is offering a brand-new Hydrogen-powered train [10], whereas the EcoTrain is a hybrid modernization of an existing combustion powered vehicle [11-13]. An obvious question arises:

Which train architectures can provide environmental friendlier and future-oriented alternatives to the DMU?

This paper aims to address this question and shows that aerospace methodologies can successfully be transferred to the railway industry. The following section provides a literature review of work that has been done in this area as well as a review of the appropriate methodology.

In 2014, Pagenkopf and Kaimer from the German Aerospace Center have published a techno-economic paper about the alternative propulsion concepts for railway vehicles [8]. They examined two DMU alternatives, a battery electric multiple unit (BEMU) and a fuel cell multiple unit (FCMU) and have shown that for an expected decrease in hydrogen and battery costs, similar life-cycle costs as the DMU can be achieved. Due to the long recharging time and range limitations, BEMUs are seen as less flexible compared to FCMUs. However, questions about reliability and availability remain unanswered. According to the paper, the readiness of certified components, their suppliers, as well as the spreading of the required infrastructure, may be barriers to introduce those alternative concepts.

A consortium of DB RegioNetz Verkehrs GmbH, the Erzgebirgsbahn, the TU Chemnitz, the Fraunhofer IVI and TU Dresden have advanced a hybrid retrofit to the regional standard class 642 railway vehicle [11-13]. 16 of these types operates within the Erzgebirgsbahn between Chemnitz and Cranzahl on a relatively mountainous route. Before the modernization, they were powered by two diesel hydro-mechanical propulsion units, one in each of the two sections. To reduce emission and noise, 11 hybrid concepts were found. A significant amount of these variants exists due to the combination of different propulsion systems for each section and possible coupling between those. The four most promising architectures were rated by experts with respect to 12 criteria. The concept with the highest overall score was selected and further analyzed as well as dimensioned for the specific track requirements.

Crawley et al. [14] have described the System Architecture paradigm which allows to define architectures with a set of decisions and search comprehensively through the design space using a model-based approach. It originated as a discipline in civil engineering and since then has proven its success, among others, in early phases of complex aerospace engineering tasks [15]. So far, this methodology is mostly used in the aerospace industry, but as we show in this paper, it is highly adaptable to any other complex engineering task.

Industry independent information about the potential of hybrid vehicles can be found in references [16-24]. Domain specific information about the railway sector is listed in [25-31]. Using the information on the literature review we can formulate our specific objectives with the to-by-using framework:

The specific objective of this work is **to** identify non-dominated architectures that have the potential to provide environmental friendlier and future-oriented alternatives to the DMU **by** (1st , section 2) defining the architectures with decisions and visualizing them, (2nd , section 3) developing an easily understandable model to evaluate and optimize each viable architecture, (3rd , section 4) making sense of the results to inform the decision-making process **using** the System Architecture methodology originated from the aerospace industry. The final section 5 concludes our work and provides an outlook.

2 Defining the plausible design space

According to Crawley et al. [14], each system can be represented by a set of decisions. We use a morphological matrix with the main architectural decision as rows and the possible options as columns to define the architecture of a railway vehicle (see Table 1). The options for a certain decision must be mutually exclusive. An architecture is then defined by choosing one option for each decision. They do not have to be from the same column. For this paper, the system under consideration is the propulsion system, which can be decomposed into three functions, *Driving*, storing electric energy on board (*EStoring*) and producing electric energy on board (*EProducing*). Each function can be executed by up to six different forms.

For example, a pure combustion engine vehicle can be defined by choosing *Diesel Engine* for *Driving*, *None* for *EStoring* and *EProducing.* For a permanent electrified vehicle, the last two decisions are the same, but the *Driving* function is fulfilled by an *Electric Engine*. The hybrid EcoTrain is represented by *Driving* = *Electric Engine*, *EStoring* = *Battery* and *EProducing* = *Diesel Engine* [11]. For the hydrogen powered Coradia iLint, the first two functions are achieved by the same form, but the electric energy is produced by a *Fuel cell* [10]. A combinatorial enumeration (= product of the last column) would lead to 96

Table 1: Architectural decision matrix

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	#
Driving	Diesel Engine	Electric Engine	Diesel + Electric Engine				4
EStoring	Battery	Flywheel	Compres sed Air	Battery + Flywheel	Battery + Compres sed Air	None	6
EProducing	Diesel Engine	Turbine	Fuel cell	None			4
							96

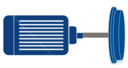
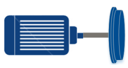
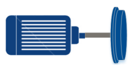
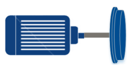
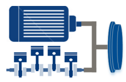
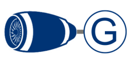
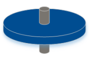
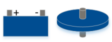
possible architecture, but not all of them are feasible and reasonable. In total, we found four constraints:

1. If there is no electric engine, it is not reasonable to have any electric production, storage or supply.
2. If there is a hybrid parallel drive, it is not reasonable to have no energy storage capability
3. If there is a diesel engine on the hybrid parallel drive, it is not reasonable to have an additional Diesel engine, turbine or fuel cell to produce electric energy
4. If there is turbine or fuel cell energy production, an interim storage is needed

After encoding these four constraints into a Design Structure Matrix (DSM) matrix with all options as rows and columns, we can represent the remaining 28 architectures in a matrix (see Table 2).

The rows encode the second decision *EStoring* from Table 1 with its six options. Starting at the top, the first pictogram stands for the option *Battery*, the second one for *Flywheel*, the third one *Compressed Air*, the fourth, *Battery + Flywheel*, the fifth *Battery + Compressed Air* and finally *None*. The decisions about the function *Driving* and *EProducing* are presented by the columns. Starting from the left, the two pictograms in the first column indicated an *Electric Engine* drive with *Diesel Engine* energy production. In the second, third and fourth, the drive remains an *Electric Engine*, but the energy production is done by a *Turbine*, a *Fuel Cell* or *None* respectively. The fifth column shows

Table 2: Overview of the 28 architectures defining the design space

	Driving ->						
	EProducing ->				None	None	None
EStoring		**1 BEMU**	**2**	**3 FCMU**	**4**	**-**	**5**
		**6**	**7**	**8**	**9**	**-**	**10**
		**11**	**12**	**13**	**14**	**-**	**15**
		**16**	**17**	**18**	**19**	**-**	**20**
		**21**	**22**	**23**	**24**	**-**	**25**
	None	**26**	**-**	**-**	**27 EMU**	**28 DMU**	**-**

a traditional DMU unit with no energy production and a *Diesel Engine* for driving. The right column shows a parallel drive of diesel and electric engines but no energy production. The "-" in the cells indicates that the combination of row and column yields to an infeasible combination. Excluding those, the residual architectures are numbered from #1 to #28. The traditional architecture EMU and DMU are represented by architectures #27 and #28, respectively. Pagenkopf [8] investigated the hybrid alternatives BEMU and FCMU which correspond to #1 and #3. The EcoTrain is a serial hybrid shown here as architecture #1.

In this section, we have developed a matrix representation that allows to easily understand and communicate the possible architectures. The pictograms encode the options unambiguously and new concepts can be generated to enlarge the design space - making it more likely to find "better" solutions. The following section describes our approach to develop a model including the optimization procedure and the objective functions used to rank the architectures.

3 Model

To explore the design space, we consider a specific track with a constant energy and power demand. Depending on the architecture, the energy is distributed among the subsystems with the design variables x_k as shown by Figure 1. For example, if the storage

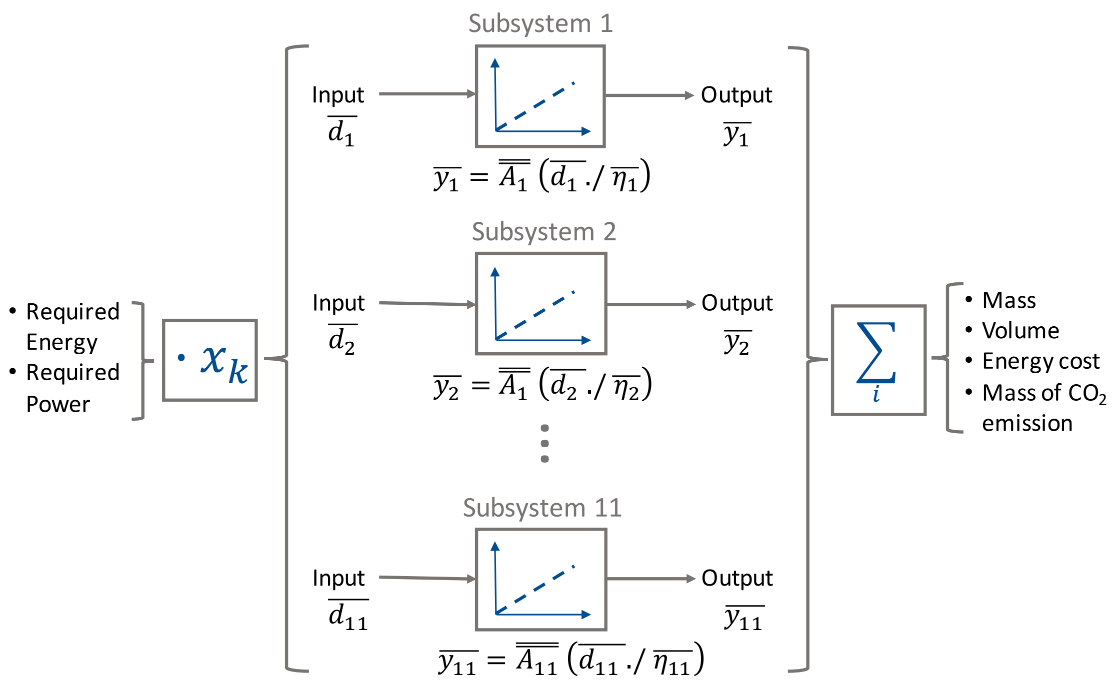


Figure 1: Schematic drawing of the design space exploration methodology

option *Battery + Flywheel* is selected, a design variable distributes the total required stored energy between those two storage options to minimize the objective functions.

The subsystems are the 11 different pictograms from Table 2. We take the mass, volume, energy cost and CO_2 emission as the metrics of interest (= objective functions). The relationship between the input and output variables is modeled linearly. This can be written mathematically as $\bar{y} = \bar{\bar{A}}\left(\bar{d} \,./\, \bar{\eta}\right)$ with the element wise division "./" , $\bar{d}$ being the input variables, $\bar{y}$ the output variables, $\bar{\eta}$ the power and energy efficiencies of the subsystem and $\bar{\bar{A}}$ a matrix of constants. The input vector contains the fraction of energy and power. The output vector lists the four variables of interest. The output of all subsystems is summed up to result in the objective functions of the architecture.

The matrix $\bar{\bar{A}}$ has a dimension of $o\ x\ p$ with o being the number of output variables which is in our case 4 and p being the dimension of the input vector which is 2. This would result in up to 8 unknown constants for each subsystem. These numbers have the unit of the output variable divided by the corresponding input. For example, the linear relationship constant between the mass and energy has $[kg/J]$ in SI-units, which is the inverse of the energy density. The energy cost and mass of CO_2 emission do not depend on the power of the system but solely on the energy. Hence, there are 6 remaining entities of matrix $\bar{\bar{\mathrm{A}}}$ which are shown in Table 3 with their units.

This matrix must be filled for each of the 11 different subsystems represented as a different pictogram in Table 2. For some, these values were not available on subsystem level and the subsystems had to be unfolded to their components. We used Object-Process-Diagrams (OPDs), where processes are shown by blue ellipses and objects with green rectangles. A black triangle decomposes objects and arrows are result links between process and objects. Lines with unfilled circles are instrument links connecting processes with their instrumental objects. For further information on OPDs, the reader is referred to Dov Dori’s textbooks [32, 33]. Figure 2 shows an example unfolding of the turbine subsystem.

The subsystem consists of four physical objects, a liquid tank, a turbine (compressor, combustion chamber, and power turbine), a generator and an AC/DC inverter. Each of these four objects enables one process to run. The processes affect, consume and produce

Table 3: SI-units of the 6 entities in the $\bar{\bar{A}}$ matrix

	Mass	**Volume**	**Energy cost**	**Mass of CO_2 emission**
Energy	$[kg/J]$	$[m\char`^3/J]$	$[€/J]$	$[kg/J]$
Power	$[kg/W]$	$[m\char`^3/W]$	-	-

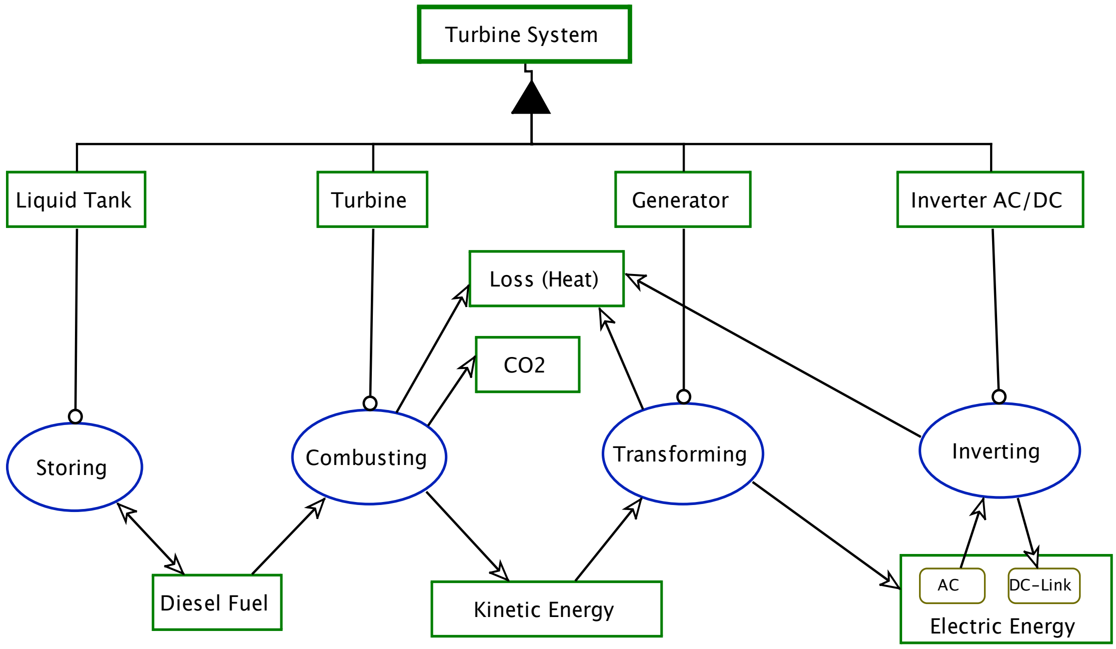


Figure 2: Example of an OPD for the turbine subsystem

objects. The *storing* process affects the *diesel* by keeping it in place and requires a *liquid tank* to do so. The *combusting* uses a *turbine* consumes *diesel* and produces kinetic energy, CO_2, and losses in form of heat. The kinetic energy is transformed with a generator to electric energy. An inverter inverts electric energy from the AC state to the DC-Link state. Both, the transforming and inverting process produces losses. With these diagrams, we can detect the components needed for each system to execute its function. For each of these components, a matrix like the one described could be filled. Summing those entities results in a subsystem matrix $\bar{\bar{A}}$ allowing to calculate the output vector $\bar{y}$ by a given input vector $\bar{d}$. The data for populating the 11 matrixes were extracted from references [8, 34-47].

As shown in Figure 1, the variables x_k distribute the required energy and power between the subsystems. They are used as design variables to find the minimum objective functions for each architecture. To comply with energy conservation, the sum of these fraction must equal one: $\sum_k x_k = 1$. These variables do not only distribute the energy among the subsystems, but furthermore there is a fraction for the refilling at each station as well as a fraction of energy recovered by regenerative braking. In total, there are 7 of those design variables with 5 breaking down the energy and 2 distributing the required power. A genetic algorithm (GA) varies those design variables in order to minimize the architecture with respect to two chosen metrics. This can be any combination of the four outputs. Furthermore, the optimization strategy allows to include constraints on mass and volume. These are often prescribed by the physical layout of the train.

Table 4: Validation of our model with the three architectures, BEMU, DMU, and FCMU, reference data from Pagenkopf [8]

	Mass in [kg]	**Volume in [m^3]**	**CO_2 emission in [kg]**	**Energy cost in [€]**
#4: BEMU	15,800	10	657	197
Model ->	16,013	11.21	517	155
Relative Deviation ->	**1%**	**12%**	**21%**	**21%**
#28: DMU	15,800	24	6,799	3,204
Model ->	14,319	22.44	6,803	3,432
Relative Deviation ->	**9%**	**6%**	**0%**	**7%**
#3: FCMU	15,800	26	15,214	5,019
Model ->	14,096	25.43	12,828	4,229
Relative Deviation->	**11%**	**2%**	**16%**	**16%**

We validated our model against the model developed by the German Aerospace Center [8]. The four outputs of the three vehicles, BEMU, DMU, and FCMU are calculated with our model and compared. We use the relative deviation as a measurement for the accuracy. The validation is shown in Table 4. For the CO_2 emission of electric current, we use the German electric current mix with 500 g/kWh [48]. Note that for each architecture a different scenario was used and hence the outputs are not comparable between each other. The deviation for mass and volume are below 12 % and for CO_2 emission and energy cost below 21 %. These values are highly acceptable for a first conceptual design space exploration.

In this section, we showed how a linear parametric model was built and which design variables and objective functions are used to optimize each architecture. A validation against another model showed satisfactory accuracy. In the subsequent section, we show optimized results for two specific cases. The first is unconstraint and optimized towards minimum volume and mass. The second is mass and volume constraint and optimized towards CO_2 emission and energy cost.

4 Result and Discussion

Besides the energy and power demand, there are 8 additional requirement variables which have to be set to allow optimization of the architectures. They are listed with the corresponding values in Table 5. We use the railway route from Ulm to Oberstdorf in Germany as a reference case. The 130 km route has 13 intermediate stops with a useable stop time of around 60 s per station [8]. At the station, the energy storage system can be refilled with a maximum power depending on the capacity. We assume this value to be

Table 5: Used requirement variables defining the scenario

Power	500,000	[W]	Delta charge battery	0.6	[-]
Required Energy	1.42E+09	[J]	CO_2 emission electric current mix Germany	1.39E-07	[kg/J]
number of stations	13	[-]	Energy cost Diesel	3.53E-08	[€/J]
Refilling time at station	60	[s]	Energy cost Hydrogen	7.64E-08	[€/J]
Fraction of recovered energy due to regenerative braking	0.1	[-]	Energy cost electric current	4.17E-08	[€/J]

1.5 kW/kWh for batteries, 10 kW/kWh for compressed air and 100 kW/kWh for the flywheel. We consider that regenerative braking results in 10 % reduction of the overall required energy. The maximum delta charge of the battery is set to 60 % in order to achieve reasonable lifetimes [8, 20-22]. The CO_2 emission of the electric current mix in Germany is estimated to be 500 g/kWh [48]. The energy costs are taken from Pagenkopf for the year 2017.

Under this exemplary scenario, two different cases are presented. The first one is without further constraints on volume and mass and optimized towards minimum mass and volume. The second has constraints on mass and volume and is optimized for minimum CO_2 emission and energy cost.

4.1 Case 1: Unconstraint and optimized towards minimum mass and volume

The first case is an optimization of the architecture without additional constraints. Figure 3 shows the two objective functions with the mass of the architecture in [kg] on the

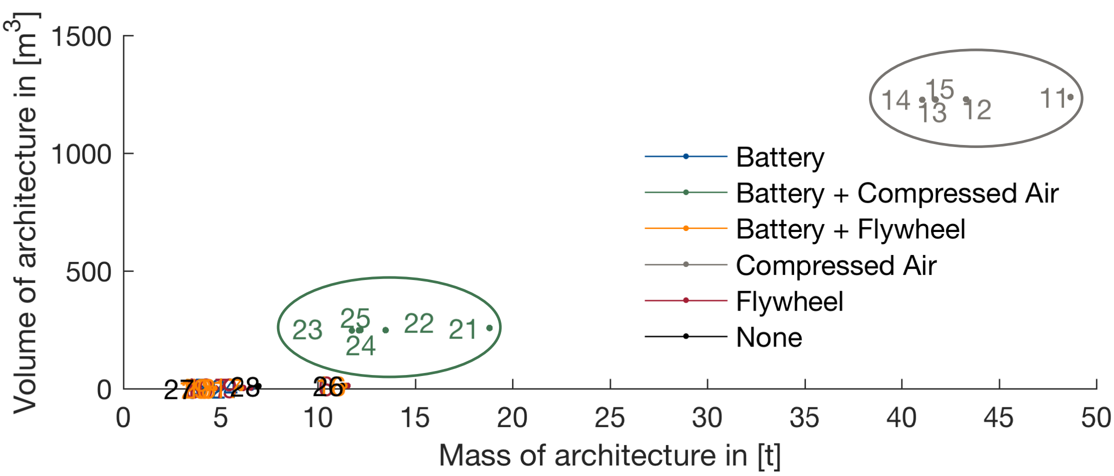


Figure 3: Volume and mass for the optimized architectures, colored by the energy storing decision

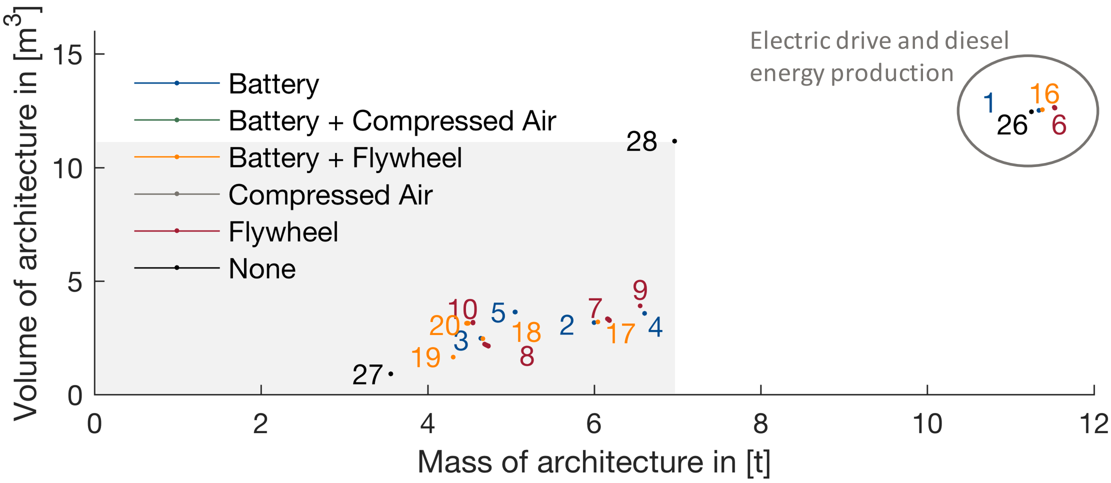


Figure 4: Zoomed-in on the remaining 18 architectures

abscissa and the volume in [m^3] on the ordinate. Each architecture is colored according to its energy storing option.

Across all architecture, it can be observed that the volume of the system increases with increasing mass. It becomes as high as 50 t and 1250 m^3. These are an order of magnitude higher than values for DMUs and hence seen as not feasible. The two groups with high values in both dimensions have compressed air storage. Adding a battery helps to reduce the size and weight, but they are still far above comparable architectures. We can argue with these data that the 10 architectures with compressed air storage have infeasible volume and mass for our specific scenario under investigation. A zoomed-in version of the remaining 18 architecture is shown in Figure 4.

The EMU architecture #27 is the smallest and lightest concept. This makes sense since no additional production and storage subsystem is required and the electric motor has a high energy and power density. The DMU, #28, has around twice the mass and ten-times the volume (the EMU system does not include the transformer and the main switch, which would move the mass and volume of EMU and DMU closer together). This is due to the lower energy and power density as well as the additional required transmission and fuel tank. In the top-right, there is a group of four architectures with similar volumes and masses. They have different storing options but equal driving and production configuration, an electric engine for driving and diesel engine for energy production. This configuration is often called serial drive. Compared to a parallel drive (#5, #10, #20), the additional generator adds volume and mass. We assume the parallel drive is split into two different wheel sets and therefore no additional planetary gear is needed. Furthermore, the scaling parameters are different. In a parallel drive, not only the energy can be split between the electric and diesel engine but also the power. This results in a smaller scaling of the subsystems of a parallel drive architecture. For example, half of the power demand is provided by the electric traction motor, the other half by a diesel traction motor. In a serial configuration, both systems have to be scaled for the maximum power. If the objective of the investigation is to modernize an already existing DMU-train, the gray rectangle in Figure 4 marks the area for which hybrid architectures exist which have smaller masses and volumes. This allows to directly replace the DMU power-pack without reinforcing the train structure or making additional space. The mass and volumes of serial systems are above the one for DMU and hence would possibly require more space and reinforcements.

4.2 Case 2: Mass and volume constraint and optimized towards minimum CO_2 emission and energy cost

In contrast to the first case, the architectures are not optimized towards minimum volume and mass but these two variables taken as constraints. Under these conditions, the GA minimizes the CO_2 emission and energy cost. This case applies for a modernization of existing trains with new propulsion systems where the volume and mass are prescribed. For the hereinafter results we assume a mass and volume limitation of 12,000 kg and 15 m^3, respectively. As we have seen in the previous case, the compressed air storage option has infeasible dimensions and weights. Therefore, the algorithm does not converge for these 10 architectures (#11-15, #21-25). The remaining 18 architectures are plotted in Figure 5 with the CO_2 emission in [kg] on the ordinate and the energy cost in € on the

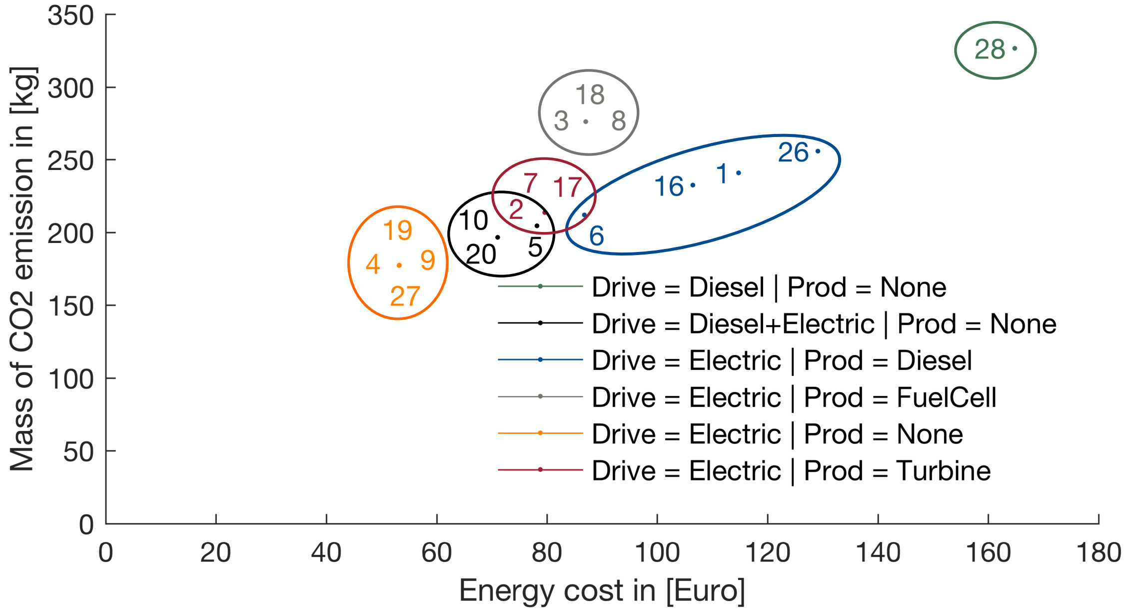


Figure 5: Mass of CO_2 emission versus energy cost of the optimizable 18 architectures, colored by the driving and producing decisions

abscissa. The data is colored by the driving and production decisions (columns of Table 2).

First, similar to Figure 3 and Figure 4, there is an almost linear relationship between the mass of CO_2 emission and energy cost. This means that reducing the energy cost results in a reduction of CO_2 emission as well, giving the operators a financial incentive to invest in environmental friendlier propulsion systems. Architectures with the same driving and energy production subsystems are encircled by an ellipse. The DMU is on the top-right and has the highest energy cost as well as CO_2 emission. On the opposite, the EMU together with the other pure electric architectures reduces the amount of CO_2 emission by almost 50 % and the energy cost by around 70 % compared with the DMU. The four groups in between those two extremes, have significant storage capacity and refilling fractions in order to take advantage of the lower energy cost and green gas emission of electric energy. However, the fuel cell (gray) compared to the turbine (red) and diesel (blue) energy production has similar energy cost but higher CO_2 emission. For the optimization, we assumed that hydrogen is produced by electrolysis with an efficiency of 60 % and then converted back to electric energy by the fuel cell with an efficiency of 50 %. This results in a 30 % end-to-end efficiency (not even include storing losses). The low overall efficiency consequences the relative high CO_2 emission which is almost in the area of the DMU. However, the FCMU allow to reduce local CO_2 and providing a future-oriented solution for an expected increase in the proportion of the renewable energy production in the German electric current mix. This would result in a lower CO_2 emission of the hydrogen production process. Comparing the parallel drive (black) and the serial (blue) drive options, the system optimization reveals lower energy cost and emission of the parallel drive. The parallel system's lower mass (caused by the scaling effects discussed in case 1) leaves space and mass for larger storing subsystems. The larger the storage, the more energy can be stored at the start of the route and recharged at each station. For these charge processes, electric energy with its lower energy cost and CO_2 emission is used. Hence, the architecture can be optimized closer to the EMU. The same effect can be observed when comparing the energy production option turbine (red) and diesel (blue). The higher energy density of the turbine results in lower mass and volume of the production subsystem, leaving space and mass for a larger storing subsystem. Note, that the used cost metric on the abscissa does not consider infrastructure, investment, replacement and maintenance costs. These contributions, as we have shown in section 1, shifted the EMU to be more expensive than the DMU – even if the energy costs are significantly lower.

5 Conclusions and Outlook

In this final section, we summarize our work, conclude it with the main insights and give an outlook on how our approach can be used. The first section 1 has demonstrated that alternative architectures for future trains are needed and that the System Architecture paradigm is the appropriate method to represent and generate new concepts and explore the originated (usually large) design space. The approach was applied in section 2 and section 3 described the model to evaluate and optimize the alternatives. In the preceding section 4, the results of two exemplary cases were presented and discussed. We gathered the following insights of the design space consisting of the 28 architectures:

- The compressed air storage option results in volumes and masses orders of magnitude higher than the other alternatives
- There are numerous hybrid architectures with lower masses and volumes than the DMU and hence modernization of DMU trains is possible without the need for structural reinforcements
- A parallel drive configuration is smaller and lighter than serial drive and therefore the remaining mass and volume budget can be used for larger storage subsystems, leading to lower CO_2 emission and energy costs
- The relatively low end-to-end efficiency of fuel cell energy production results in greenhouse gas emissions close to the DMU. However, a future reduction in the CO_2 emission of the German current mix is expected, reducing the CO_2 emission of the hydrogen production. In addition, no local CO_2 emission can be realized and the hydrogen can be produced during periods with high wind energy and solar energy production, making it a possible element of stabilizing the electric current network.

With this paper, we have discovered a set of most promising architectures, consisting of the pure electric drive #4, 9, 19 and 27 as well as the parallel drive alternatives #5, 10 and 20. To find the single most suitable architecture, the model needs to be extended to investigate each architecture in more depth. This extension may include (1) the integration of a dynamic drive model to have route specific energy and power demands, recuperation possibilities and usage data of auxiliary devices, (2) assessment of life-cycle costs (investment, infrastructure, replacement, maintenance), and (3) the inclusion of distribution possibilities across multiple cars.

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