Encouraging a Modal Shift to Passenger Railway Transportation: A Case Study in Adaptable Rolling Stock Interior Design

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Abstract: Continued urbanization continues to pose one of the greatest challenges to the environmental, economic and social sustainability of society. The modal split between transport modes has remained relatively unchanged in recent decades. This suggests that the level of private car use will lead to even more congestion in urban areas. Therefore, a modal shift from private to public transport should be further encouraged. One of the decisive quality characteristics for preferring public transport over private car use, such as passenger railway transportation, is the level of comfort. However, one of the main challenges for railway operators is the change in demand for capacity during peak hours and the demand for comfort during off-peak hours. The purpose of this study is to investigate the applicability of adaptable design in rolling stock interior to facilitate adaptations using case study research. The proposed design concept was evaluated and compared with current coach interior configurations using grey relational analysis. The case results showed that the design concept was adaptive by providing more options to meet the different needs of comfort and capacity. In addition, three new guidelines were identified that can generally serve as functional guidelines in the development of more adaptable assets in use to further encourage a modal shift.

Keywords: sustainable mobility; modal shift; adaptable design; public transport

1. Introduction

As commuters return to the roads following the COVID-19 era, continued urbanization still poses one of the greatest challenges to the environmental, economic and social sustainability of society. As the modal split between modes of transport has remained relatively unchanged in recent decades, this suggests that the level of private car use will lead to even greater congestion and air pollution in urban areas, despite the increase in electrification of cars. Therefore, a modal shift from private to public transport still needs to be further encouraged and facilitated.

High-capacity transport modes such as railway passenger transportation is perceived to play an important role in creating a sustainable future for transport in Europe [1]. This is also recognized in the Sustainable and Smart Mobility Strategy 2030 in making the European transport system more sustainable, smart and resilient [2]. However, in a context where daily car use is still a habitual choice for a wide majority of the population, the quality of the alternatives to individual motorized vehicles is a major factor in encouraging modal shift.

Different research directions are followed to increase attractiveness of public transport to further encourage a modal shift, such as park-and-ride systems [3–5], digital journey planners for users [6] and travel support [7]. This study follows the research direction which recognizes that traveller requirements are fundamental in effecting modal shift measures and that the effects of public transport quality attributes on encouraging modal shift need...
to be taken into consideration. Batty et al. [8] highlighted that a number of challenges exist in successfully effecting any notable level of modal shift from private to public transport. To face these challenges, operators should consider that public transport needs to ensure focus is given to the quality attributes most effective at encouraging modal shift.

One of these quality attributes is a high level of comfort [8]. This can change travel from a derived demand into a valued activity, making it a more enjoyable experience than travelling via private car. However, one of the key challenges for railway operators is the change in capacity demand during peak hours and comfort demands in off-peak hours. For being able to offer both capacity as well as comfort to railway passengers, rolling stock needs to be adaptable to meet the changing demands in these two states. The aim of this paper is to investigate how the interior of a train coach can adapt to peak and off-peak hours during train operations using design science research in a single case study.

The remainder of this paper continues as follows. Section 2 elaborates on the concept of adaptable design. It provides the foundations for the design approach presented in Section 3. The results of the case study are described in Section 4. Section 5 proposes a method to evaluate and measure the adaptability in terms of capacity, versatility and comfort of rolling stock interior. The paper concludes with a discussion and several suggestions for future adaptable designs in rolling stock to further encourage a modal shift to passenger railway transportation.

2. Design for Adaptability

The increased rate of technological changes and sustainability challenges forces railway operators to reconsider their design approach to enable rolling stock to adapt to changing circumstances more often, and ‘in use’, to meet the requirements of railway passengers. Technological changes require systems to be more robust and more adaptable [9]. The idea of adaptable design for the development of products was proposed by Gu [10]. The definition of adaptability is not consistently used [11], but adaptable design can be considered as a paradigm that aims at creating solutions and products that can be easily adapted to different requirements [12]. Since the introduction of the adaptable design concept, many adaptable design methods have been developed in the past decade [13]. It has gained attention not only in the domain of product development but also in robotics, building design and other scientific fields [14,15]. As described by Fricke et al., [16], Schulz et al., [17], Fricke and Schulz [18] and Greysel et al. [19], one of the first applications of Design for Adaptability (DfA) in mechanical engineering was presented early in the 2000s, with a strong focus on changeability. Four aspects of changeability are distinguished: flexibility, agility, robustness and adaptability. These four aspects describe a system ability to cope with changes within itself or its environment [20]. Simply stated, flexibility represents the property of a system to be changed easily, with low effort and without undesired effects. Agility represents the property of a system to rapidly implement necessary changes. Robust systems deliver their intended functionality under varying operating conditions without being changed. Adaptability characterizes the ability to adapt itself towards changing environments delivering its intended functionality. The main focus of this paper is on adaptability and, more specifically, on adaptable designs.

Adaptable designs are aimed at developing designs that can cope with various circumstances. Adaptable designs can be categorised into design adaptability and product adaptability depending on the subject of adaptation [21]. Design adaptability refers to the use of a similar design, with minor changes, to create different products. Product adaptability refers to the ability of a single physical product to be used for different service requirements. In product adaptability, the adaptation task is usually performed by the user to achieve various functions or to enhance its performance in different states [10]. Furthermore, product adaptabilities can be classified into specific and general product adaptabilities [10]. When adaptabilities and their probabilities can be predicted, the product can be designed to accommodate these specific product adaptabilities. On the contrary, when new requirements cannot be predicted, the product can be designed to only have
some general product adaptabilities. The general guidelines for specific product adaptability, as proposed by Hashemian [21], provides a starting point for adaptable designs (Table 1).

Table 1. General guidelines for specific product adaptability, as proposed by Hashemian [21].

<table>
<thead>
<tr>
<th>#</th>
<th>Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Utilize the existing features and components to achieve extra functionalities.</td>
</tr>
<tr>
<td></td>
<td>Define the primary functional requirement and the additional functional requirements for versatile product design. Find low-cost solutions for achieving additional functional requirements in the original design.</td>
</tr>
<tr>
<td>3</td>
<td>Provide extra features and functionalities in a design for possible future needs.</td>
</tr>
</tbody>
</table>

The objective of adaptable design is to extend the utility of products and their designs [21]. The utility of a product can be extended over the course of time, or it can be extended in the scope of applications. The former is called “sequential adaptation”, and the latter is called “parallel adaptation”. Parallel adaptability of a product means that the same product can be set up in various ways to perform different functions. This typically results in the development of versatile products which are capable of performing several functions [21]. A product is designed for versatility if adaptations from one function to another occur frequently. Therefore, the product is designed to facilitate adaptations that do not require significant alteration of the product and often involve simple procedures which can be performed by the user.

Besides the expected benefits of designing for adaptability, it may also have some disadvantages. As Schulz et al. [17] discussed in the implementation of changeability, the trade-off between the right price to pay or the right amount of time to spend to achieve the expected benefit of adaptability is a critical consideration. Designing a product for adaptability might result in additional costs, more safety risks or more downtime for maintenance. Therefore, it is recommended to decide if, and to what extent, adaptable design is desirable.

3. Research Approach

This research is based on a single case study [22] in The Netherlands. Its main purpose is theory elaboration (extension) on adaptability in rolling stock interior design, which may also be applicable to other domains. The use of a single case allows for greater depth but limits the generalizability of the conclusions. The research design is based on the Design Science Research Methodology (DSRM) as proposed by Peffers et al. [23]. The DSRM process includes six steps: problem identification and motivation, define the objectives for a solution, design and development, demonstration, evaluation, and communication [23]. Communication of the design is considered to be presented by means of this paper.

In a conventional design process [24], a product is designed for a nominal set of functions and consists of a product planning, conceptual design, embodiment design and detailed design. In the adaptable design paradigm, products can also be adapted to different or additional functions beyond their ‘normal’ operation mode which may require a different approach. Nevertheless, in designing for product versatility, the additional functional requirements are treated the same way as the original functional requirements. Therefore, designing the new train interior was considered to be a conventional product design process.

3.1. Design Strategy for Rolling Stock Interior

Rolling stock consists of different layers which change at different rates. The sheared layered approach (6S) for adaptability in buildings, as introduced by Brand [25], can also be used to characterize the layers in rolling stock (refer to Figure 1). Brand argues that any building is actually a hierarchy of pieces, each of which inherently changes at different rates. From a building perspective, the site is eternal and the structure is good for 30 to
300 years. The skin changes every 20 years. The services (e.g., wiring, heating) change every 7 to 15 years. The space planning depends on the type of building and changes every 3 to 30 years. Stuff changes almost continuously. The more layers that are connected, the greater the difficulty and cost of adaptation [25]. Similarly, the lifespan of the structure of rolling stock is 30 to 40 years, with a refurbishment and modernization of skin, services and space planned to be conducted at half of its lifetime [26].

Figure 1. Layers of rolling stock, based on Brand [25], with expected lifetimes.

In general, most interiors hold some level of adaptability. For instance, seats and tables are moveable to adapt to different situations. However, in rolling stock interior, it is not possible to leave interior elements and furniture unattached mainly due to strict safety regulations. Movable interior elements could still be included by fixing them on a track or a pivot point. However, allowing railway passengers to change the interior by sliding or rotating interior elements in a running train still does not comply with safety regulations and may result in additional maintenance costs. Moreover, it is also questionable whether railway passengers would make use of these adaptations since it would require physical effort.

As a result, the responsibility for such adaptation shifts from passengers to employees. This reduces the effectiveness and responsiveness of the adaptability and adds extra costs and time necessary to complete the adaptation. Furthermore, adaptations between the states of peak and off-peak hours occur frequently (twice a day), which may implicate the development of versatile products. These products facilitate adaptations that do not require significant alteration of the product and often involve simple procedures which can be performed by the user. Instead of integrating more adaptability into the interior, the interior itself can also be made more adaptive by making its elements more adaptable.

The design strategy of this study is based on the concept of product adaptability with rolling stock interior as the subject of adaptation. The two states of peak and off-peak hours in train operations are, to some extent, predictable. Therefore, the adaptability of rolling stock interior can be considered as specific parallel product adaptability. In design methods for specific adaptabilities, the overall strategy is to provide features which are needed for a ‘predetermined’ set of adaptations. The functional requirements of both states in rolling stock interior are well known during the design process. As a result, the interior can be designed to deliver multiple functions including the original functional requirements and the additional functional requirements. The adaptable design methodology [21] consists of four main activities which will be described in more detail in Section 4:

(a) Define the original design problem;
(b) Identify the set of target adaptation tasks. This process utilises forecast information on versatility;
(c) Develop a functional structure that includes both original functional requirements and the requirements of future adaptations;
(d) Design the physical structure of the product according to the applicable methods and guidelines of specific adaptability.

3.2. Data Collection and Methods Used

Data was collected and analysed in the different design stages and started with 10 open interviews with key stakeholders, personal observation during peak and off-peak hours when travelling by the VIRM train, and historical quantitative and qualitative
reports provided by the case organisation. Key stakeholders included maintenance experts, operating staff, interior design experts, infrastructure operators, health and safety experts and railway passengers. Continuously, railway passengers are surveyed by the case organization to find out how they experience their train journeys. This information was especially useful during the design phase, where ideas were invented, developed and visualised by sketching and rapid modelling for discussions with the stakeholders. For digital sketching, mood boards and variation exploration, Adobe Photoshop CC was used. The information and insights from the analysis together with the requirements and specifications provided the foundation for ideas and concepts to be developed and discussed with stakeholders. In the concept development phase, multiple concepts have been designed using in-context 3D modelling. The programs used to develop both the individual seating concepts and the full interior concept further into a 3D model for render visualisation and 3D printing are SolidWorks 2018 and Keyshot 6. Three focused design sessions were held with experts from the case organization to tackle more specific design problems. A 3D-printed scale model was created to obtain a better and more accurate sense of the feasibility and spaciousness of the interior concept, and it was intensively used in the evaluation process of the design concept with key stakeholders.

4. Results

4.1. Case Study Introduction

The VIRM trains (translated from Dutch: the lengthened interregional rolling stock) are a series of electric multiple-unit double-deck trains operated by the Nederlandse Spoorwegen (NS). Initially designated DD-IRM, the first trains entered service in 1994 as three- and four-car sets. These were extended into four- and six-car sets not much later after they came into service (VIRM). Rolling stock requires refurbishment and modernisation when the train has reached half of its operational life. At the end of 2016, the refurbishment of the fleet of 81 first-generation VIRM sets started with a programme which concluded in 2020. The refurbishment of the second- and third-generation VIRM trains follow a similar pattern. Besides maintenance work on the electrical, mechanical and hydraulic technology, work on the train body also needs to be performed, both on the inside and on the outside of the train [27]. This provides an opportunity to increase adaptability to address future challenges. Figure 2 shows an example of the current space and interior of the VIRM trains (before refurbishment).

4.2. Define the Original Design Problem

Defining a design problem in adaptable design means being mindful of what information is needed for designing for adaptability. As defined in Section 2, designing for specific parallel product adaptability requires that all situations are known and present.
According to Hashemian [21], the first step is to analyse the different states, and needs within those states, in which the product has to function. Once the states have been indexed, it is necessary to elaborate on what makes the states different from one another and what role the product should have in each state.

In the VIRM trains, the main difference between the two states of peak and off-peak hours (Figure 3) is the amount and type of users. During peak hours, the number of passengers is high, mainly commuters. In off-peak hours, the number of passengers is low, and more passengers travel for leisure. The design problem has been defined as follows: in order to facilitate both states of peak and off-peak hours, the train interior should be able to adapt to the different number of users by being able to offer more capacity when it becomes more crowded and more comfort when it is less crowded. Additionally, the interior needs to be able to adapt to the different type of users by allowing different activities to satisfy their needs to facilitate the modal shift from private to public transport.

Figure 3. Design for adaptability in train operations.

4.3. Identify the Set of Target Adaptation Tasks

The second step in the adaptable design methodology [21] is the identification of target adaptation tasks. The emphasis of this activity should be on the relationship between the user(s) and the product. The user analysis can be extended to include how much time and costs the user(s) are able or willing to invest in the product. This data is relevant because it will provide limitations in both complexity and duration of the interaction with the product. Furthermore, it is necessary to analyse what functions are critical to users and to which functional state(s) they belong. These functions can then be translated to adaptation tasks of the product. The outcomes of all the functions may vary between different types of users.

In the VIRM case, railway passengers (users) are not able to invest much time and effort in the product, since rolling stock interior is a shared semi-public space and passengers spend a limited amount of time here. As a result, the product has to be able to be understood and properly used by communicating clear affordances. If the product is misunderstood, it needs to be redesigned and simplified. The extent of adaptation tasks is limited to the willingness of the type of users who have the lowest amount of time and effort to invest in the interaction with the product. The results of the user analysis, partly based on the train experience monitor [29], showed that the most critical functions and aspects of the interior to leisure users is primarily feeling welcome and being able to find a place. For commuters, the opportunity to perform different activities within the same place is a high-valued function. Both groups value the cleanliness of the interior and the feeling of appreciation.

The main target adaptation tasks for rolling stock interior design identified are:

- Being able to adapt to the different states by providing the opportunity to switch between comfort and capacity;
- Being able to be used for continuously changing activities.
4.4. Develop a Functional Structure That Includes Functional Requirements

After identifying adaptation tasks, it is recommended to divide and group the set of requirements of the different situations in a functional structure as identified in the design problem analysis. If correctly performed, it should be possible to find conflicts in the requirements of the different situations, for evaluating specific trade-offs. Each trade-off should then be carefully considered to achieve a fair balance between the situations.

Figure 4 presents the functional structure of the two states (peak and off-peak hours). Based on the requirements of both states, there is a consistent trade-off between comfort and capacity. In addition to that, there were also trade-offs for silence and spoken areas, luggage space and leg space, cleanliness and user experience.

<table>
<thead>
<tr>
<th>Functional requirements off-peak hours</th>
<th>Functional requirements peak hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>When there is more empty space during off-peak hours, it should be possible to use in order to provide more comfort.</td>
<td>Due to a high amount of users, more capacity is necessary during peak hours.</td>
</tr>
<tr>
<td>Facilitate social interactions and activities to take place.</td>
<td>Facilitate enough privacy and silence to feel comfortable to work undisturbed.</td>
</tr>
<tr>
<td>Allow for people to sit together and inclusion.</td>
<td>Allow for individuality and exclusion.</td>
</tr>
<tr>
<td>Facilitate enough seating space to provide a more comfort.</td>
<td>Facilitate enough workspace to comfortably work with a notebook or laptop.</td>
</tr>
<tr>
<td>The surroundings should be experienced as interesting and engaging.</td>
<td>The surroundings should be experienced as calm and undistracting.</td>
</tr>
</tbody>
</table>

Figure 4. Functional structure of requirements of peak and off-peak hours.

4.5. Design the Physical Structure of the Product

As discussed in Section 2, three design guidelines (1–3) for specific product adaptability [21] have been adopted as a starting point for the new design of the VIRM interior. During the design process, these guidelines have been extended to fit the context of rolling stock interior design. Furthermore, three new guidelines (4–6) have been identified in the design process of rolling stock interior that may generally serve as functional guidelines in the development of adaptable products in use.

4.5.1. Utilize the Existing Features and Components to Achieve Extra Functionalities (Guideline 1, Existing Features)

The first guideline is aimed at identifying needs which require nearly the same features or aspects. It attempts to combine them into one concept or element. This provides adaptability in function since the same product can be used for multiple needs. For example, the lounge seat in rolling stock interior is appropriate for relaxing, which is the most performed activity in the train, and talking. The features associated with these activities are nearly the same, which allows for an efficient combination. As a result, it should not add much complexity. To the contrary, the combination of relaxing and working is much less efficient because the required features are not the same, which means it needs to adapt to more different situations.

Making a seating configuration suitable for talking requires seats to directly face each other or to be at a 90-degree angle. Designing the lounge area (Figure 5) to be used for both relaxing and talking will make it more functional and desirable for users. However, the disadvantage of combining the needs of relaxing and talking is that the additional sound made by talking can disturb users who want to relax. This illustrates the need to
reflect on the advantages and disadvantages caused by the attempt to combine features and components into one concept or element.

Figure 5. The lounge area.

4.5.2. Define the Primary Functional Requirements and the Additional Functional Requirements for Versatile Product Design; Find Low-Cost Solutions for Achieving Additional Functional Requirements in the Original Design (Guideline 2, Prioritise Requirements)

This guideline is meant to emphasise the functions which are used the most or are most critical to start with. This forces a decision in the focus of the product, which leads to an explicit design goal. Prioritising functionalities of the product also gives an indication of how accessible every function should be, which allows the product to become less complex in use. If a function is not used frequently or is less valued by its users, it is not necessary to be very accessible; on the contrary, if something is frequently used or vital, then it should be easily accessible [30]. This means the prioritisation of the functions should be established by analysing the frequency of the usage of the function and what impact it has on the user experience. When there are multiple types of users, it is logical to prioritise the needs of the most frequent user. Likewise, when there are multiple frequent users, common needs should be identified and prioritised.

The second part of the guideline states specifically that low-cost solutions should be found for additional functional requirements. However, there is no reason why additional functional requirements should always need to be low cost. If a functional requirement can be realised effectively by a more expensive option, it can be a valid decision to go for the option which best satisfies the need via this additional functionality, instead of a low-cost option.

In the VIRM case, this guideline has been applied to every place. The places aimed at the activity of working are a clear example (Figure 6). There are multiple requirements to create a comfortable working place. By prioritizing the primary and most critical functionalities, which are the seating position and desk space, the places fulfil their main purpose as best as possible within the constraints of the context. Additional functional requirements were defined, such as storage facility for backpacks and small bags within hand-reach (Figure 6). The additional requirements were designed and implemented after the initial design for the workplace had been established. As a consequence, the requirements had to fit both within the limitations of the context as well as the preliminary design.
4.5.3. Provide Extra Features and Functionalities in a Design for Possible Future Needs (Guideline 3, Future Proof)

Identifying future needs is difficult and always induces a risk. If a feature for a future need is left out, but the future need develops into an actual need, the product will be outdated faster. An excellent example in rolling stock interior is the opportunity to charge mobile devices and laptops. Twenty years ago, power outlets could have been included in the VIRM design as an extra feature to extend the lifespan of the interior by facilitating the future need for charging smart phones and laptops. Rolling stock interiors lacking this feature will now be outdated much faster. On the contrary, if a feature for a future need is added, but the future need does not develop into an actual need, the time and resources taken to implement it have been wasted, and it might even provide additional problems concerning maintenance or efficiency.

In the VIRM case, this guideline has not been executed to the full extent due to the scope of the design, which is aimed to facilitate short-term adaptations. Future proofing requires an extensive analysis of current trends to make more reliable predictions. Moreover, the best analysis cannot predict the future, and new features may have an adverse impact on the feasibility of the concept. However, the implementation of the ridge for mobile devices to be able to stand in the working table (Figure 7) can be considered as an accommodation of a future need as probably more work activities will be performed on smaller devices. These devices will not necessarily have support to stand by themselves.

Figure 6. The workplace.

Figure 7. Fixed and connected table.
4.5.4. Identify Limiting Factors in the Design Which Prevent the Product from Functioning Optimally in the Different Situations (Guideline 4, Limiting Factors)

In the current VIRM interior, every seat in a two-seat configuration has a table which can be tilted down to use. The table of the seat next to it is not connected to this table, and when both are tilted down, there is a gap which prevents the user from being able to work more comfortably when the seat next to the user is empty. By connecting the tables, there is more workspace and therefore more comfort when working. However, a disadvantage is that the table becomes shared and does not allow individual choice anymore. To reduce the impact of this disadvantage, only the high seats, which were already aimed at facilitating working activities, will have a fixed and connected table which cannot be tilted up (Figure 7). Other seats still do have tables which can be tilted up.

In this example, the gap between the tables is a limiting factor. It means that limiting factors can also be the absence of something (in this case material or a connection). By identifying these limiting factors in the design process, it is possible to focus on and optimise specific parts in the design without looking at the entire problem at once. In other terms, this guideline supports the designer to switch between different contextual levels to optimise the adaptable design. Solutions found at a detailed contextual level will by definition have consequences for the entire design. Therefore, the advantages and disadvantages caused by the change should always be evaluated in the context of the entire design. If the disadvantages have been identified, they can be attempted to be solved or reduced at the higher contextual level. Additionally, the new design should fit in with the rest of the design.

4.5.5. Avoid or Minimise Complexity in (Social) Interaction, since It Will Have a Negative Effect on Usability and User Experience (Guideline 5, Avoid Complexity in Interaction)

Complexity decreases the amount of flexibility because it requires higher costs in the form of effort. Since adaptable products are inherently more complex, it is recommended to aim for a reduction in complexity. In the case of designing for a (semi-)public area, it is especially relevant since complexity often also requires more time and effort from users and increases the risk of more maintenance costs. Minimizing complexity can be achieved by eliminating unnecessary features or possibility for movement, creating a simple interaction with the product. The amount of complexity of the product has been established in the analysis of the relationship between the user and the product.

In the VIRM case, this concept is clearly illustrated by the table between four seats. This category of places is mostly focused on social activities, since seats face each other and thus facilitate talking. In the concept of the interior design, the functionality of these places is increased by an extendable table (Figure 8), which allows users who are sitting at the corridor side to do more. The table is extended by a sliding motion, which is indicated by the handle integrated into the design. This interaction for extending the table is a folding motion where the extension of the table would be attached on hinges at the side. However, this interaction is usually physically more complex, and the social interaction also becomes more difficult, especially when the table is already in use. Therefore, the fold-over solution would be less adaptable because it is more difficult to use in practice.
4.5.6. Additional Functionality Can Be Achieved by Changing or Even Leaving out an Element (Guideline 6, New Functionality by Removing)

The focus of guideline 6 is about changing or removing parts or elements to create new functionality, instead of explicitly removing a limiting factor to enhance or optimise a specific functionality (guideline 4). In the lounge area of the concept design, there is a part of the sofa without a backrest, as can be seen in Figure 9. The backrest is not a limiting factor, such as an armrest or gap between the tables as discussed in guideline 4. Additional functionality in the form of more flexibility of usage can be achieved by removing the backrest. The sacrifice of the comfort of these seats gives more flexibility in use, which adds to the adaptability between the different situations. The seats can be used on either side and potentially provide more space. Besides that, the area feels less closed off and therefore safer and more easily accessible.

Figure 8. Extendable table.

Figure 9. Sofa without backrest.
5. Evaluating and Measuring Adaptable Design in Rolling Stock Interior

The new interior concept (Figure 10) is flexible in capacity and comfort due to the versatility of its elements (see for example Figure 8). The interior offers an increase of 24% in maximum capacity, amounting to 14 additional places per compartment, compared to the current interior configuration of the VIRM. The introduced concepts are high seats and a combination of corner sofas, which offer new user experiences.

![Aisle of the coach.](image)

- The new sofas provide flexibility in capacity and comfort because it can accommodate more people in peak hours and allow for different ways to comfortably sit during off-peak hours.
- The high tables allow for more comfort when working by having more desk space.
- The space between the seats, which is mandatory for getting in and out of the seats, can be used in more crowded situations to also allow people to work on the table while standing.
- Although the passenger will not be able to sit, the ability to still work on a table and not have to stand in the middle of the aisle provides comfort and the sense of a place within the interior.

Additionally, the user experience of the interior concept is more human-centred compared to the current interior. This is not only reflected in practical and functional aspects such as facilitations for smaller bags at workplaces (Figure 6) and the extendable table at the four-seat area (Figure 8), but also in emotional and sensory aspects. A clear example of this is the soft floor material under the lounge sofas (Figure 9). In order to determine the rate of adaptability, the next section proposes a method for measuring the adaptability of the new rolling stock interior design compared to the current configurations of the VIRM train.

5.1. Measuring Adaptability in Rolling Stock Interior

The aim of this research was to increase the overall adaptability of the coach to different situations based on the needs of railway passengers, thereby recognising the need for ensuring the same, or even higher comfort for the passengers. Based on the case study, three significant factors determine the effectiveness of the desired adaptability in train interior: capacity, comfort and versatility. In this paragraph, the design concepts of the upper and lower coach compartment (Figure 11) are evaluated and compared to the current upper and lower coach compartments. In the design concepts, there is only one travelling class; for the existing scenarios, the following two cases are considered: both coaches with only a second class, and also where first and second class are together. Consequently, six solutions are compared and evaluated.
Previous research identified several evaluation methods for adaptable design. Fletcher et al. [31] developed a method to evaluate adaptability of an adaptable product by comparing the actual structure of the product with its ideal structure. Cheng et al. [32] developed a structure-based approach to evaluate design by measuring essential adaptability and behavioural adaptability. Li et al. [33] introduced new adaptability evaluation measures to identify the optimal adaptable design based on evaluation to different design candidates. To measure the adaptability of the six candidates and to find the best design candidate, the grey relational analysis method [34] was adopted. This approach is particularly appropriate in case of a small dataset; it offers the opportunity to bypass the demands of the normal statistical analysis, while at the same time giving reliable results by comparing different evaluation measures.

The capacity value is based on the number of travellers in one coach (standing travellers are not considered or counted in any design candidate, except for the travellers at the standing place with an individual table offered by the concept solutions). The versatility is evaluated counting the number of different solutions offered (i.e., seat with individual table, couch seat) in the same coach. Finally, the comfort value is calculated using a Likert scale system with a range from 0 (minimum grade) to 5 (maximum grade) (Figure 12). Since the major problems are related to the daily travels in the rush hours, the comfort during peak hour travel is considered more relevant than the comfort in off-peak hour travel; consequently, it is weighted 0.2 times more (60%) than the off-peak hour value (40%).

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Concept lower compartment</th>
<th>Concept top compartment</th>
<th>Current lower compartment (both classes)</th>
<th>Current top compartment (both classes)</th>
<th>Current lower compartment (2nd Class)</th>
<th>Current top compartment (2nd Class)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity [n travelers]</td>
<td>68</td>
<td>66</td>
<td>43</td>
<td>48</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Versatility [n solutions]</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Comfort peak/off-peak hours [0-5]</td>
<td>4.5</td>
<td>3.7</td>
<td>3.2</td>
<td>3.7</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Comfort peak hours [60%, 0-5]</td>
<td>4.5</td>
<td>4</td>
<td>3.5</td>
<td>4</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Comfort off-peak hours [40%, 0-5]</td>
<td>4.5</td>
<td>3.5</td>
<td>3</td>
<td>3.5</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 12. Overview of the values of the adaptability measures for each candidate.
Finally, the three adaptability measures (capacity, versatility and comfort in peak/off-peak hours) have been weighted with the support of NS experts and traveller surveys as follows in order to address the right priority in the design evaluation:

\[ W_{\text{capacity}} = 45\%, \ W_{\text{versatility}} = 20\%, \ W_{\text{comfort}} = 35\% \]

The capacity and comfort are considered as a paramount priority for improving the adaptability of the train.

5.2. Application of the Grey Relational Analysis to the Six Candidates

The required steps for running the grey analysis are summarised below, also as described in Li, Xue and Gu (2008). Based on these steps, the grey analysis is performed on the six candidates:

a. Creating the Decision Matrix \( D \) and the Standard Series \( A_0 \)

\[
D = \begin{bmatrix}
68 & 5 & 4.5 \\
66 & 3 & 3.7 \\
43 & 4 & 3.2 \\
48 & 3 & 3.7 \\
50 & 4 & 2.2 \\
50 & 3 & 3.2
\end{bmatrix}
A_0 = \begin{bmatrix}
68 & 5 & 4.5
\end{bmatrix}
\]

b. Normalising the Decision Matrix \( D_0^* \) and the Standard Series \( A_0^* \) to a dimensionless system.

\[
D_0^* = \begin{bmatrix}
1.000 & 1.000 & 1.000 \\
0.920 & 0.000 & 0.652 \\
0.000 & 0.500 & 0.435 \\
0.200 & 0.000 & 0.652 \\
0.280 & 0.000 & 0.435 \\
0.280 & 0.000 & 0.435
\end{bmatrix}
A_0^* = \begin{bmatrix}
1.000 & 1.000 & 1.000
\end{bmatrix}
\]

c. Discovering the differences between the normalised Decision Matrix \( D_0^* \) and the standard series \( A_0^* \) and establishing the \( \Delta_{\text{max}} \) and \( \Delta_{\text{min}} \)

\[
\Delta_0 = |D_0^* - A_0^*| = \begin{bmatrix}
0.000 & 0.000 & 0.000 \\
0.080 & 1.000 & 0.348 \\
1.000 & 0.500 & 0.565 \\
0.800 & 1.000 & 0.348 \\
0.720 & 0.500 & 1.000 \\
0.720 & 1.000 & 0.565
\end{bmatrix}
\]

\[
\Delta_{\text{max}} = \begin{bmatrix}
1.000 & 1.000 & 1.000
\end{bmatrix}
\Delta_{\text{min}} = \begin{bmatrix}
0.000 & 0.000 & 0.000
\end{bmatrix}
\]

d. Finding the grey relational coefficient matrix \( \gamma_0 \) adopting a distinguish coefficient \( \zeta = 0.5 \), as suggested by Li et al. [33].

\[
\gamma_0 = \begin{bmatrix}
1.000 & 1.000 & 1.000 \\
0.862 & 0.333 & 0.590 \\
0.333 & 0.500 & 0.469 \\
0.385 & 0.333 & 0.590 \\
0.410 & 0.500 & 1.000 \\
0.410 & 0.333 & 0.469
\end{bmatrix}
\]
Calculating the Degree of Relation $\Gamma$ for each design candidate with the established weighting factors and ranking them. The Design candidate with the highest value of Degree of Relation satisfied the initial requirements (Figure 13). Both designed concepts show significantly higher ratings on adaptability based on the factors of capacity, comfort and versatility.

<table>
<thead>
<tr>
<th>Degree of Relation</th>
<th>$\Gamma_1 = 1.000$</th>
<th>$\Gamma_2 = 0.661$</th>
<th>$\Gamma_3 = 0.414$</th>
<th>$\Gamma_4 = 0.446$</th>
<th>$\Gamma_5 = 0.401$</th>
<th>$\Gamma_6 = 0.415$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranking</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

**Figure 13.** Degree of relation and final ranking of the candidates.

### 6. Discussion and Implications

This section discusses the results and highlights the limitations of the work. Traditionally, rolling stock interior is to a large extent determined by the original equipment manufacturer and limited by strict safety regulations. However, the need for adaptability is increasing to meet passenger needs and to facilitate a modal shift. Railway operators need to consider adequate responses to deal with fast-changing environments and to facilitate a modal shift. They cannot solely rely on manufacturers, and they need to position themselves in the driver’s seat to determine to what extent adaptable design should be incorporated in future designs of rolling stock. By following a structured design approach using principles from adaptable design, the case organisation was supported to (re)consider new interior concepts to respond to the different needs in capacity and comfort during peak and off-peak hours.

However, the proposed interior concept also has potential disadvantages in terms of additional (operational and maintenance) costs, impact on safety and regulations and impact on the lifecycle of rolling stock. These barriers have not been further examined as part of this study. To further investigate the barriers to adopting the proposed design concept, an expert elicitation survey could be conducted in future research. Furthermore, future research could also provide a mathematical or experimental justification for the effectiveness of the proposed design solutions and its impact on daily operations.

The key factors of versatility, comfort and capacity, which determine the effectiveness of adaptability in rolling stock design, are specific to the case and cannot be considered as general attributes of adaptable designs of rolling stock interior. Furthermore, measuring comfort depends on many attributes and is therefore difficult to evaluate objectively. Nevertheless, it is one of the critical factors in offering service quality to railway passengers. By considering adaptability as an essential design characteristic for rolling stock interior, it will not only strengthen the capability of railway operators to meet the changing needs of railway passengers in peak and off-peak hours to facilitate modal shift, but may also increase the lifetime of rolling stock interior in the long term. It reconsiders rolling stock not only as individual ‘assets’ but incorporates the perspective that rolling stock learns from its passengers. Like Brand stated [25], “age plus adaptivity is what makes a building come to be loved. The building learns from its occupants, and they learn from it”.

The proposed design concept has proven to be more adaptable but remains a challenging task due to the many (safety) regulations in railway transport and interactions between the different layers of rolling stock. Based on the operationalisation of the concept of Design for Adaptability in rolling stock interior, three new guidelines (focus on limiting factors, avoid complexity in interaction, and new functionality by removing) were identified that may generally serve as functional guidelines in the development of adaptable assets in use in facilitating a modal shift.

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