DIGITALISATION AND SUSTAINABILITY IN CABIN DESIGN: SYNERGIES AND DEPENDENCIES

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Abstract

Aviation is subject to intense competitive pressure, impacting operations, aircraft development, and their cabins. These effects are nowadays largely determined by topics such as digitalisation and sustainability. This article highlights synergies and interdependencies between the two topics and shows how additional value can be created when considered together.

Keywords: cabin, sustainability, digitalisation, aviation, synergies

1. Introduction

Increasing competition in the transport sector leads airlines to offer their customers even more services. Rising fuel costs, taxes, and charges increase pressure and the need for innovation throughout the aircraft. The cabin, as the interface between the airline and the passenger, plays an essential role because it makes the first impression of the competition between airlines and is crucial for the well-being of the customer and the associated experience [1].

With the increasing relevance of sustainability through regulatory initiatives such as the European Green Deal of the European Union, factors that positively influence the sustainability of the aircraft and its cabin are becoming more relevant for development and the entire life cycle. The Green Deal, presented in 2019, aims to reduce greenhouse gas emissions to net zero by 2050 [3].

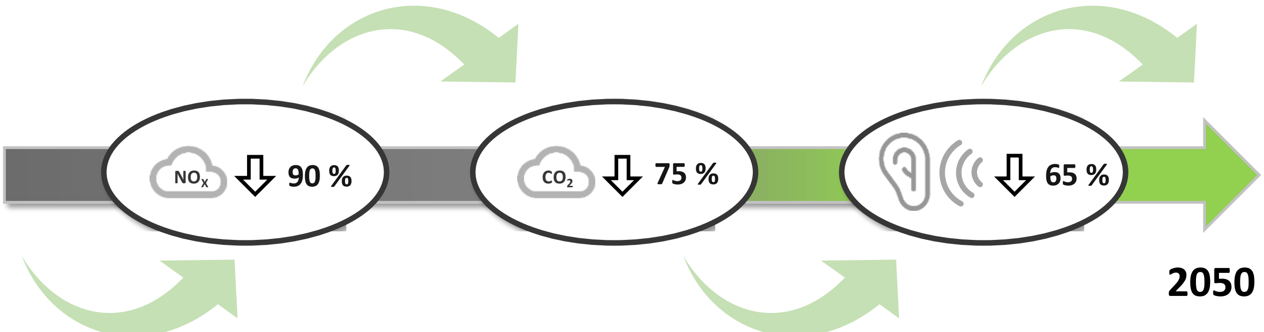


Figure 1 Sustainability goals to reach by 2050 as set by the Green Deal

As a result, emissions need to be reduced during the manufacturing and operation of aircraft while reconciling the rising number of sustainability requirements with economic efficiency [3]. The concomitant challenges are characterised by the great importance of data in general and development or runtime data in particular. Therefore, the associated need to digitalise processes and the entire system is also essential. Because of regulatory requirements, the aircraft system must change drastically. As shown in Figure 1, for example, CO_2 emissions are set to be reduced by 75% and noise emissions by 65% by 2050 to achieve the objectives set. While developing new technical solutions for propulsion and lift plays an important role, the cabin, with a 10-20% share of emissions, likewise has potentials that should not be neglected but provide additional leverage points on the road to net zero [4]. As the usage phase of aircraft accounts for an essential share of emissions due to their long service life, reducing weight is the most significant lever for cabin development. It should be noted that digitalisation and the consideration of sustainability are unavoidable topics for future developments. Therefore, this work will focus on the resulting synergies between these two topics concerning cabin development and explain these with different examples.

2. Fundamentals

In order to highlight possible synergies between the two aspects, this section briefly discusses the fundamental need to increase sustainability as well as digitalisation in relation to the aircraft cabin. This discussion forms the foundation for the subsequent identification of synergetic potentials and dependencies in the next section.

2.1 Digitalisation

Digitalisation plays a decisive role in many areas of development. There are various effects of digitalisation on the development process of products. These elements will be discussed below, focusing on model-based approaches and their advantages for aircraft cabin development.

The digitalisation of product development encompasses a variety of technologies and methods that make the entire development process more efficient and precise. One technology that has been used for many years is CAD software. It enables the creation of detailed digital models of aircraft cabins and their monuments and components. Its use simplifies the visualisation, adaptation and optimisation of designs. Many parameters are defined in the design or redesign of components, which significantly influence the final product. The digitalisation of processes makes it easier to make changes, and optimisations can also be made according to new aspects, such as sustainability. Approaches such as design for assembly or disassembly can be simulated in digital space and tested before being transferred to the real process [5]. The resulting cost savings, also in the context of sustainable processes, should be emphasised here [6].

In this context, virtual reality (VR) and augmented reality (AR) can allow developers to interact with the product even more intensively. Above all, the increased use of VR and AR offers immersive experiences that enable developers and stakeholders to experience the cabin in a virtual environment. Hence, it improves understanding and decision-making and can also be used to test functions early on in a digital mock-up and study the impact on the customer [7].

Another aspect in this context is using simulations that test the product to be developed for different scenarios and conditions without creating physical prototypes. These tests can be carried out from the material to the finished product level. They also offer the opportunity to test development decisions at an early stage and, if necessary, redesign them [8]. In recent years, the increasing computing power of computer clusters, in particular, has made it possible to use more complex and better simulation models, which also offer great potential to analyse structures in more depth and reduce the mass of parts even more [9].

Historically, the management of the various technical data was mainly document-based. Due to the increasing complexity of systems and the ever-increasing multidisciplinary development, handling the occurring data in this way becomes increasingly challenging. As a result, model-based approaches that map the information using system models are becoming increasingly important. Using system models, as is known from model-based systems engineering, development data can be mapped utilising modelling languages, tools and methods. They utilise a single source of truth and offer traceability of data correlations. The cabin can be modelled with its many different systems and interactions, from the structure to the electronics to the software. This promotes a better understanding of the interactions and dependencies between the various system components. Furthermore, these models can be used to integrate requirements management and to document the subsequent verification and certification directly in the model using suitable tests [10][11][12]. It was shown that using a systematic approach to establish these models positively influences the comparability of different models from different domains. The data basis created using these computer-readable system models can also be used and expanded for other applications. Due to the standardised modelling language, the models can be easily extended and adapted for a wide range of applications [13]. If these models are also fed with real-time data from the final product and data is simultaneously sent back to the real asset, this is referred to as a digital twin. The digital replica of the physical cabin created in this way enables continuous monitoring and optimisation of the cabin throughout its entire life cycle [14].

While some development information is available in digital PDF files or printed documents required for certification, current ways to acquire up-to-date geometric information often facilitate 3D-scanning processes [15]. With long lifespans of up to 30 years, aircraft are regularly equipped with new cabin interiors to face wear and tear and stay up to par with changing customer needs [16]. The process of retrofitting aircraft and designing the new cabin requires detailed knowledge of the specific aircraft and access to its documentation. This is mainly done by extensive manual work, which is time-consuming and results in interferences during the first attempt to install the new cabin into an airframe because of high uncertainties [15]. While there are current approaches for an increased digitalisation of the associated processes [17], this can mostly be seen as an enabler platform that allows for more digital services. For the digital documentation of the occurring interdependencies, some existing approaches are utilising system models, as originated from MBSE [18].

2.2 Sustainability

The European Union sees the aviation industry as "an invaluable asset for Europe", generating a turnover of 238 billion € in 2021, corresponding to roughly 1,6 % of the EU's gross domestic product of 14,5 trillion € in that same year [19]. This economic contribution highlights the vital role of the aviation sector in fostering economic growth, job creation, and regional connectivity within Europe. At the same time, however, the global aviation industry is responsible for around 2% of the worldwide CO_2 emissions [19]. Facing climate change and customers who are becoming more and more sustainability-oriented, the European aviation industry aims to reduce CO_2 emissions by 75% by 2050 [20]. This ambitious target aligns with broader European and international efforts to achieve net zero emissions and limit the rise in global temperature under the Paris Agreement. Achieving such a reduction will require a multi-faceted approach, including advances in aircraft technology and operational improvements.

While alternative aircraft and propulsion concepts must be found to achieve this goal in the long term, short-term solutions are also needed to increase the sustainability of the existing fleets since the average service life of an aircraft is 20 to 30 years. Possible short-term solutions include aerodynamic enhancements and weight reduction strategies using advanced materials. Operational improvements, such as optimised flight routes, enhanced air traffic management, and more efficient ground operations, can also significantly reduce emissions. Especially for the improvement of existing fleets, the aircraft's cabin and cargo are an excellent option, representing 10-20% of an aircraft's overall emissions and, in contrast to the primary structure, being replaced multiple times during an aircraft's lifecycle [4], which allows for a possible faster implementation of new cabin-approaches and technologies, compared to the aircraft itself.

On the one hand, there is potential for the use of alternative, renewable material components. For example, using bio-composite materials in cabin interiors may not only reduce weight. However, it may also decrease the reliance on petroleum-based products, thereby lowering the carbon footprint of the aircraft. Innovations in materials science, such as developing high-performance, recyclable composite materials, can improve the sustainability and cost-effectiveness of cabin retrofits. On the other hand, there is potential for optimising and improving the various processes and procedures in and related to the cabin [21]. For example, between 0.63 and 1.81 kg of cabin waste is produced per passenger on long-haul flights, of which almost a quarter (23.4%) is unconsumed, untouched food [22]. This means there is potential for savings by, for example, choosing food early before boarding so that loading can be more targeted.

2.3 Consolidation of Digitalisation and sustainability

At this point, digitalisation in aviation plays an important role as an enabler of sustainability. On the one hand, a wide range of information is required to assess sustainability. On the other hand, digitalisation facilitates collecting, processing and analysing large amounts of data. Advanced analytics and machine learning may help to analyse this data in depth and gain insights that can lead to more efficient operations and enable operators and passengers to make informed decisions.

The following section thoroughly examines possible interactions and dependencies between sustainability and digitalisation.

3. Digitalisation and Sustainability: Synergies and Dependencies

This chapter describes the push and pull factors between sustainability and digitalisation and provides different examples to illustrate the connections between these two essential topics.

3.1 Push- and Pull-Factors between Sustainability and Digitalisation

Recently, two independent trends and aspirations have been observed in aviation. However, domains and topics aside, digitalisation plays a significant role in the progress of processes and the emergence of new products and services. With the increased focus on environmental effects and climate change, sustainability has become another major factor in improving existing processes and the development of new products.

While, at first glance, these two factors seem to be independent of one another, a closer look reveals synergies and dependencies that, when considered mutually, can further increase the effect and reach of the respective approaches. Generally speaking, at least two of the following categories of interdependencies can be identified: these are discussed in the following and depicted in Figure 2.

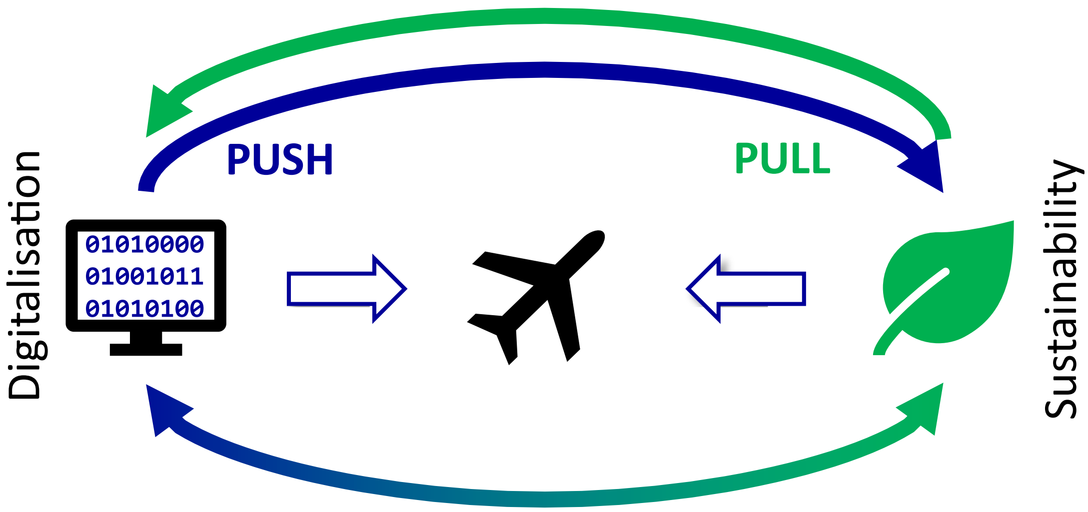


Figure 2 Visualisation of the described concept of interdependencies between digitalisation and sustainability.

Digitalisation Pushing Sustainability

In this category, the main goal of an effort is not aiming towards sustainability but something different, like process optimisations. Here, digitalisation plays an important role, for example, in establishing a digitally documented and monitored process. The motivation solely or predominantly lies within the direct effects of digitalisation, such as saving costs or creating transparency, with sustainability not playing a targeted initial goal. However, with the digitally documented or monitored system, adding parameters that allow for analysis and, based on this, the improvement of factors regarding sustainability is a comparably small and easy step. Thus, targeted digitalisation enables and pushes approaches for increased sustainability.

Sustainability Pulling Digitalisation

This category can be seen as the vice-versa of the above. The goal of an effort is to increase the sustainability of a product or process. The current state must be analysed and documented to create a baseline and identify suitable starting points to improve sustainability. If done accordingly and digitally, this can be seen as a resulting improvement in digitalisation that can be used for other purposes. In this case, the targeted improvements regarding sustainability are initially required, hence pulling digitalisation efforts.

Based on the general description of these concepts and their application in the development of aircraft cabins, the following questions arise:

- Which digitalisation and sustainability synergies can be used when developing new aircraft cabins?
- Is sustainability pulling digitalisation, or are there existing digitalisation approaches that can also improve sustainability?

Four exemplary applications are presented, describing potential benefits regarding sustainability and digitalisation and how these aspects interdepend.

3.2 Model-based representation of the passenger service unit

A model-based representation of the product family of a Passenger Service Unit (PSU) already contains the product structure of all components and their development data. This existing model can be used as the basis for a life cycle analysis and later enriched with the resulting sustainability data. The life cycle analysis (LCA) enables a holistic view of the environmental impacts that occur during the entire life cycle of a PSU - from raw material extraction, production and use through to disposal or recycling. By integrating the LCA into the existing model, precise and well-founded statements can be made about the ecological footprint of the PSU. The enriched sustainability data can cover various aspects, such as energy consumption, CO_2 emissions, water consumption and waste generation. This data is valuable not only for the internal evaluation and optimisation of PSU products but also for meeting external requirements, such as compliance with legal environmental regulations and sustainability certificates. In order to carry out an LCA, a significant challenge is to collect data for the entire life cycle.

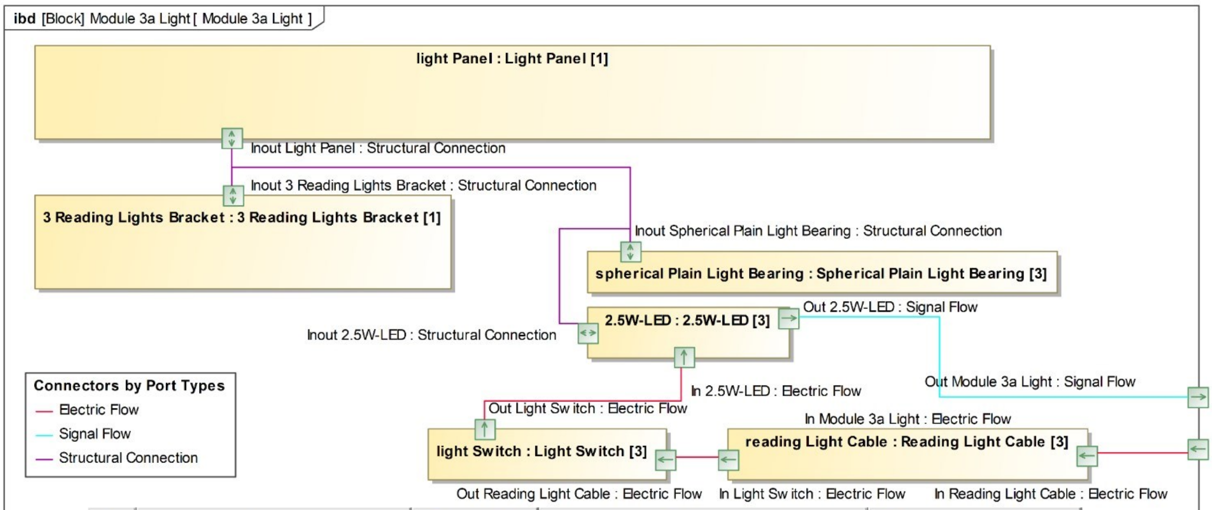
The use of system models can help in this area. A key aspect of model-based approaches is the ability to simulate and validate product variants as early as the development phase. Virtual tests and analyses allow potential problems to be identified and rectified early, reducing development costs and time. In addition, the model-based visualisation enables improved collaboration between different departments and partners, as everyone can access a standardised and always up-to-date model. This promotes transparency and efficiency throughout the entire development process.

If they have already been used for development, these approaches can be extended to provide the data required for the LCA. The system models represent the structure and behaviour of systems in models. These computer-readable models can be used further for various simulations and provide a basis for extracting and using the information externally.

In Figure 3, the light module of a PSU is modelled. The upper part of the figure shows the module's structure with the individual components, such as the light panel or the 2.5W LED and the connections and interfaces of the individual components. The lower part of the figure shows the extension of the parameterisation of the individual components. For example, the mass in kilograms, the material used, or the energy consumption during use in watts are shown here. On the one hand, this information can be extrapolated in a simulation of the usage phase in the system model to a total consumption for the LCA analysis; on the other hand, it provides the data basis as a database for the sustainability analysis.

By utilising existing digital system models, the data search for the LCA can be significantly simplified. If these models are already created with a sustainability assessment in mind, further synergies can be generated here. The resulting LCA results can also be fed back into the product development process to make future generations of PSUs more environmentally friendly and sustainable. For example, the results could provide information on which materials and components can be replaced by more environmentally friendly alternatives or how production processes can be optimised to use resources more efficiently.

A model-based approach extended with sustainability data can support the implementation of digital twins - digital replicas of the PSUs that collect and analyse real-time data from operations. This enables precise monitoring and maintenance of the units, as well as optimising operating processes and predictive maintenance. By utilising these advanced technologies, companies can continuously improve their products and services and adapt them to the market's changing requirements.



#	Name	Mass [kg]	Material	Energy Consumption
1	C 2.5W-LED	0.005	Glass, Semiconductor	2.5
2	C Light Panel	0.05	Thermoplast	0
3	C Spherical Plain Light Bearing	0.01	Thermoplast	0
4	C Reading Light Cable	0.002	Copper, Elastomers	0
5	C 3 Reading Lights Bracket	0.015	Metal, Thermoplast	0
6	C Light Switch	0.005	Thermoplast, Copper	0

Figure 3: Internal model of a PSU lighting module and its component parameters for the life cycle assessment.

The continuous updating and expansion of the model with real-time data from the production and usage phase provides a dynamic and always up-to-date basis for strategic planning and decision-making. Companies can thus react proactively to changes and new requirements, contributing to increased competitiveness and improved positioning in the market.

3.3 More precisely monitoring tank fill levels

More precise monitoring of the fill levels of freshwater tanks enables airlines to refuel according to demand and thus save weight and fuel. At present, however, fill levels are only roughly determined, especially in older models, so refuelling is also carried out roughly and conservatively, meaning that a considerable amount of excess fresh water is usually carried. This leads to unnecessary additional weight and, therefore, additional kerosene consumption and emissions.

Integrating accurate digital sensors into the aircraft's water systems is necessary to enable more precise water level monitoring. It will allow continuous measurement of water level consumption patterns during the flight. By analysing this data, airlines can gain accurate insights into actual water consumption, which can vary depending on flight duration, passenger volume and specific routes. More precise information, in turn, allows airlines to refuel fresh water more in line with demand. Instead of filling the water tanks to maximum capacity for each flight, they can adjust the refuelling more precisely for each journey based on expected consumption (Figure 4). This means significantly less water can be required on short-haul flights with fewer passengers than on long-haul flights. By fine-tuning the water load, airlines can avoid carrying excess weight, resulting in significant fuel savings. Finnair, for example, gained annual fuel savings of 100 tonnes by adjusting the standard water uplift volume [23].

In addition, the introduction of demand-oriented water refuelling can increase operational efficiency. Airlines can optimise their ground handling processes and reduce the time and resources required for water refuelling. This efficiency gain can contribute to faster turnaround times and improved adherence to flight schedules, increasing overall service reliability.

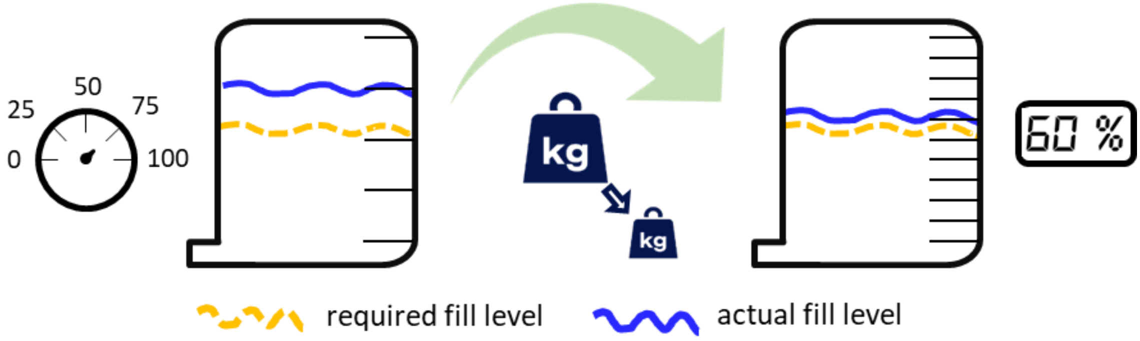


Figure 4: More precise tank fill level monitoring allowing for a better match of required and actual levels

3.4 Bring-your-own-device In-Flight-Entertainment (BYOD-IFE)

A significant driver for sustainability within the cabin is the weight of the installed components and the effect on the fuel efficiency. Especially with the lever of the long lifespan, thus time in operation, every weight that can be spared impacts the overall required fuel and resulting emissions. While inflight entertainment is important today, at least on long-haul flights, increasingly more passengers also bring their smartphones or tablets with them. So, using these available devices might be an option, especially for no-frills-airlines. With the bring-your-own-device concept, passengers can use their existing devices to access the in-flight entertainment. Instead of installing a screen and the concomitant electronics and cables in each and every seat on the aircraft, power sockets and access to a wireless network are provided to allow the devices to get charged and provide access to the media centre. Both power sockets and wireless network equipment are already installed in many modern aircraft. Instead of the screen, an adjustable tablet- or smartphone holder is integrated into the seats, allowing personal devices to be mounted to the seats. An airline app provides access to the media database hosted abroad. Passengers with no personal device could be supplied with one from the airline.

Figure 5: Schematic of the Bring-Your-Own-Device-IFE Approach

Figure 5 shows a schematic of this Bring-Your-Own-Device concept, which replaces permanently installed screens with portable and often personal tablets. The reduction of the number of installed components and the required data lines can have a beneficial effect on the overall weight of the cabin. While a detailed calculation of all devices is needed, it can be postulated that there is a benefit regarding the total accumulating weight. Considering that aircraft are equipped with seas for up to 150 (typical Airbus A320), or even 350 to 400 passengers (typical Airbus A350), this small weight reduction per seat can scale considerably.

3.5 Demand-Orientated loading

Despite the weight of the installed components, as described in the section above, the weight of the onboard supplies affects fuel efficiency, emissions and, thus, sustainability. The goal is to match the demand of the flight and the loaded supplies of food and beverages in the best possible way. While statistics and experience can play an important role in deciding what to bring aboard in what quantity, an idea could be to allow the passengers to use the time they're waiting at the gate or the online check-in process to let them already order the food or beverage of their liking. With airline-specific apps to manage their travel, perform online check-in and sometimes even track the luggage, parts of the required digital backbone are already available. Statistics to cope with unavailable choices or quickly changed demands could assist with handling remaining uncertainties. Matching the demand expected during the flight more closely with the loaded supplies will reduce the weight of unnecessarily transported goods. The benefits might not be substantial per flight, but implementing this strategy across fleets over the years might still result in relevant savings and reductions overall.

3.6 Lessons Learned from recent experiences

The holistic introduction of digital processes and tools continues to pose major challenges for many industry partners. Implementation is usually very slow due to the necessary changes to existing processes or the introduction of new software programs. The challenges described apply in particular to the use of model-based approaches, which significantly adapt the process landscape. Looking at the introduction of model-based approaches, it can be seen that this entails a high initial risk not only in terms of time but also in terms of costs, as the correct implementation and added value only take effect after a longer period of time. Nevertheless, it has been widely demonstrated in the literature and ongoing industry projects that these approaches offer great potential, especially for larger and more complex systems.

The topic of sustainability has become ever more important because of external factors like regulations, customer requirements, and the need to keep a good image of the company. Yet, it faces the challenge that many KPIs require a solid understanding of the occurring processes and the collection of new parameters and data. This data is often unavailable or can only be extracted from the company's existing data with much manual effort. As a result, the required consideration of sustainability is costly for companies and challenging to implement.

If looked at the opportunities offered by digitalisation and sustainability together, various exemplary aspects can be highlighted.

- A major advantage of digitalisation and the use of model-based approaches is that data fragments are brought together in a model, creating a linked, holistic model. This model can be used to map the data required to analyse sustainability. Accordingly, the data needed for an LCA analysis can be modelled from the outset or derived from the modelled data, and thus, carbon tracking can be established. The expected improvements can, therefore, reduce the entry hurdles that need to be overcome to introduce model-based approaches in the sustainability assessment. In this case, sustainability can be a driver for digitalisation. On the other hand, systematic digitalisation also simplifies a possible sustainability assessment and can drive sustainability.
- If the utilisation processes of various cabin elements are mapped digitally, it is easier to access data from customer interaction. For example, waste management and reducing waste during the use of the aircraft cabin can be improved. Accordingly, new services can be developed to enable a more sustainable product. Other aspects, such as the automatic recording of data or the monitoring of processes by sensors, open up further opportunities for improvement in terms of sustainability. Digitalisation is, therefore, a driver of sustainability in this area.
- Furthermore, using digital services can reduce the number of physical objects and, thus, the weight of the cabin. For example, various screens can be removed from the cabin and interfaces with customers' mobile devices can be defined and installed in the aircraft. Here again, the digitalisation of the cabin is a driver for sustainability.

To address the research questions outlined at the beginning, it is clear from the examples presented above that there are many synergies between the topics of digitalisation and sustainability. Both topics are currently very big drivers of change in the development of systems and the system itself. In the examples shown, it can be seen that both topics complement each other and that there are push and pull factors from both topics. In this case, whether one aspect pushes or pulls the other is not easily stated, but the processes are transformed in unity with a holistic and joined goal. It is, therefore, clear that both topics should be considered together in the further development of the cabin, as this is the only way to maximise the benefits and thus have a realistic chance of achieving the targets set by 2050. Indeed, current research projects are already facing these challenges. While there already is a shift to incorporate sustainability factors into the research, more work needs to be done and is highly encouraged to help reach the net zero goal by 2050.

4. Summary

The road to net zero is challenging for the mobility sectors. Aviation, especially, faces the challenge that alternative fuels might propose a solution, but they are not feasible with today's standards and not available in sufficient amounts. With the long lifespans, new technology implemented in new aircraft types will still need some time to penetrate the market. Until then, the current fleets need to find other strategies to improve their emissions and impact on sustainability. Focusing on the cabin can primarily be done by reducing weight. Here, digitalisation can help improve processes or allow for completely different strategies that benefit the sustainability of aircraft. It can be seen that there are possible push and pull factors between digitalisation and sustainability, which can be utilised to benefit both essential topics.

In conclusion, further research is needed to investigate how digitalisation and sustainability can influence, complement and promote each other. While initial findings indicate a high potential for digital technologies to enhance sustainable practices and sustainability goals to drive digital innovation, a deeper understanding of these interactions is necessary. Further research could explore the detailed mechanisms of these relations and develop frameworks that facilitate the seamless integration of digital and sustainable strategies.

Acknowledgements

The presented research is funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) as part of the sixth Federal Aeronautical Research Program (LUFO VI-2 & LUFO VI-3).

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