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Criticality and Comfort Zone Supporting Design Choices to Achieve Sustainable Requirements: The Case of Electric Aircraft

Luciana Pereira[1], Petter Krus[2]

[1]Federal University of ABC, UFABC, Brazil
[2]Linköping University, Sweden

Abstract

This paper proposes an analytical framework for estimating the domain in which a technology combination can be used in a system. To accomplish this goal, the concepts of technology critical zone and technological comfort zone were proposed in order to analyze the impact of a new technology during the design phases of a system. As a result, a framework was created that maps out the range of requirements that can lead to valid designs. This method can assist designers make decisions about technology selection by indicating the variety of requirements for which the technology can be used. Also, if a specific technology is to be used, whether it will be a cost and/or performance factor, depending on the circumstances. In this paper it is demonstrated on electric aircraft technologies, i.e., battery electric and hydrogen fuel cell aircraft. Instead of looking at the feasibility of looking at a specific range this method looks at the cost-benefit relation and a specific definition of this is introduced. This can then be used to analyze a specific technology in a certain application to map the range of valid requirements.

Keywords: Technology assessment, Design decision making, Sustainable systems, Aircraft electrification

1. Introduction

A technological system that emits no or very little carbon dioxide is referred to as "carbon-neutral" (CO2). Indeed, climate change pressures have made it mandatory that an energy-efficient design be entirely based on renewable energy [1,], [2]. This is precisely the challenge that aircraft system designers have faced when attempting to improve the energy efficiency of these systems [3],[4]. What technologies should be included in the system? How should they be assessed? Because it is perceived as complex and uncertain, this integration is extremely difficult. This is one of the aspects that necessitates efforts at innovation and experimentation in order to reduce risks and increase companies' comfort in the transition process.

One of the initial premises was that first is necessary to determine the specific set of requirements for the technology. Second, it's critical to understand what kind of system the new technology could be useful for. After examining these questions, we proposed a structure for mapping the valid region of requirements that would identify the applications in which a new technology system could be used. Simultaneously, this model should indicate which regions the design would be viable in. Characteristics such as the design parameters associated with key technological capability, application, market segment, and sustainable transition values are highlighted in this process.

We used a case study on aircraft electrification as a research methodology. Then we ran a sensitivity analysis. A linear regression model is a technique that designers can use in the development of their technological strategies to evaluate the effects on design parameters, whereas sensitivity analysis is a technique for weighing the pros and cons of various options.

Based on a set of estimations for aircraft electrification, the proposed model was validated. We examined the growing demand for electrical systems content for aircraft to map the domains of valid requirements. This technological domain was chosen due to the need to reduce emissions in the transportation sector while increasing energy efficiency. As a result, a structure based on the concepts of technology criticality, technology comfort zone, and technology sensitive zone was developed. These ideas were critical in answering the key questions about technology selection.

This paper is structured as follows. It is divided into three sections, in addition to this introductory one. Section 2 presented the research methods as well as the concepts and parameters used throughout the work. Section 3 introduced the concepts of technological criticality and mastery of the comfort zone. The model is then applied to electric batteries and to fuel cells used in aircraft propulsion in section 4. Section 6 drew conclusions and limitations, and the article concluded with some suggestions for future research.

2. Research Design

2.1 The case of aircraft electrification

The case study is a technique that can be used in a technology assessment study. In this paper, there is a keen interest in assessing the impact of a new technology during its early stages of development. The case was built specifically on electric aircraft electrification technologies. With global pressures to reduce climate change, the use of clean and renewable energy has emerged as a critical issue. The electrification of aircrafts is one way to reduce emissions. Reduce the carbon intensity of fossil fuels and increase energy efficiency are two general approaches to the transportation energy transition [5].

The economics of electrification can be divided into two parts: first, lower operating costs in existing missions compared to conventional aircraft, and second, completely new features that can open up new and profitable markets. Reduced operating costs can be achieved by substituting fuel for electricity, reducing total energy consumption, or lowering maintenance costs [6], but at a severe penalty for range and performance.

2.2 Data collection

The evaluation and selection criteria chosen are linked to metrics that enable the parameters of the alternatives to be assessed in relation to each criterion to be measured. These indicators were built from the initial data collected and the results obtained after processing them. The data source were based on secondary sources to estimate the weight of electric aircraft batteries, fuel cells and hydrogen storage.

2.3 Data analysis

2.3.1 Sensitivity analysis

Sensitivity analysis is a technique that designers can use to measure the impact of their technological strategies related to energy efficiency to the system performance. As a result, it is a method of critically evaluating decision alternatives that are interconnected. Simultaneously, it identifies sensitive variables that will influence the desired outcome.

Among the most typical uses of sensitivity analysis is in decision-making models [6]. All of the content required for the decision model in use must be capable of repeating the application of sensitivity analysis. Its goal is to assist decision makers in understanding the uncertainties, benefits, and drawbacks of a decision model's limitations and scope.

In most decision-making situations, a number of options are available. Depending on whether or not a future condition or event occurs, each alternative has some consequence. These are events that are beyond a strategist's control. In such a case, a specialist must estimate the probability of each variable occurring and choose one of the alternatives based on their evaluation criteria [5].

3. A Framework to Assess Technological Choices

How can the impact of a new technology be assessed at the design stage? To answer this question, a mathematical model was developed based on the proposition of some concepts that serve as assumptions to evaluate the design's criticality in terms of performance and cost. Suh (2001) [9] defines design as a process of mapping stakeholders demands into functional requirements, which are then structured based on design parameters. A requirement in this work is that the functional requirements be part of the requirements space, which is a function of the technology's characteristics.

One assumption is that requirements can be identified in the region where the system design is feasible. This area is known as the technological requirements space. An important requirement is that in the area of technological requirements, both technological and market issues are taken into account. We have a characteristic that affects system performance for each region. This area is known as the requirements space. In the requirements space, you can specify the technological comfort zone, the technological sensitivity zone, and the technological criticality zone.

3.1 The Characterization of the requirements space

The requirements space, which includes the concepts of technology comfort zone, technology sensitivity, and technology criticality, is critical for assessing the impact of technology in relation to a given system. The following are the criteria for determining the criticality of a technology:

- Technological advancements, such as tensile strength, energy, or specific power, should have a significant impact on system performance.
- Changing design parameters, *x*, such as size, would have less of an impact on system performance *p*.
- Significant sensitivity of design parameters *x* as a function of cost, *c*, would make increasing system performance by changing design parameters more expensive.

Requirement space

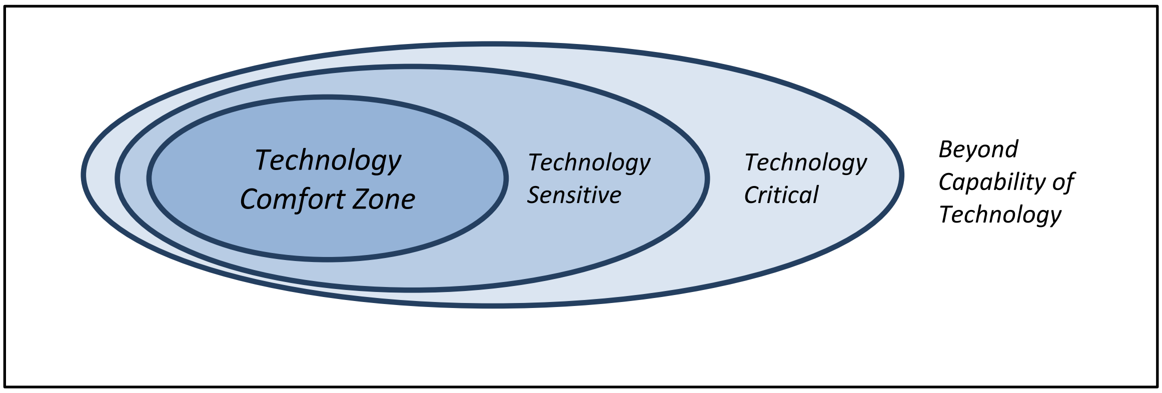

Figure 1. The requirement space.

3.1.1 Technology Comfort Zone

The technology comfort zone is defined as the area where it is simple to apply a technology. The technology comfort zone is defined as the area where requirements can be easily met and an increase in performance would just have a marginal cost. There is no need to greatly optimize the system performance in this region. As a result, it is assumed that the technology is not critical to the system's performance.

3.1.2 Technology Sensitive Zone

Technology sensitive is defined as the space in which the cost of modifying a functional feature of a system results in an increase in the system's cost, that is more than proportional to the increased performance.

3.1.3 Technology Critical Zone

Technology criticality is defined as the space in which the cost of modifying a functional feature of a system results in a steep increase in the system's cost. There are very few products in this range. One example is rockets to send satellites into orbit. To increase the final velocity of insertion, has a very steep cost. This prompts the use of multi-stage rockets to mitigate this.

4. Technology Comfort Zone concept, TCZ

4.1 The Technology sensitivity

To study criticality, it is interesting to analyze the relative sensitivity, k, around a design point, that is, we want to measure the relative impact of change in a design parameter as a function of performance. Assuming the performance can be expressed as:

$$p = f_p(x, \zeta) \tag{1}$$

the effect of an improvement of technology i on performance is here defined as the change in performance with respect to change in technology:

$$k_{\zeta,i} = \frac{\partial p}{\partial \zeta_i} \tag{2}$$

A more useful value is obtained if the normalized sensitivity is introduced. This is indicated by the relative change in performance from a relative technology improvement.

$$k_{0,\zeta} = \frac{\zeta}{p}\frac{\partial p}{\partial \zeta} \tag{3}$$

We assume that technology has high impact if this coefficient is close to unity or higher. This can be used to get an initial screening for the importance of different technologies.

4.2 Cost benefit factor

Another useful relationship is the relationship between cost and performance. The sensitivity of the performance with respect to the design variable xi related to the technology can also be expressed using normalized sensitivity:

$$k_{0,p,i} = \frac{x_i}{p}\frac{\partial p}{\partial x_i} \tag{4}$$

The system cost is assumed to be expressed in a similar way:

$$c = f_c(x, \zeta) \tag{5}$$

Here the sensitivity of the design parameter to cost is also expressed using the normalized sensitivity.

$$k_{0,c,i} = \frac{x_i}{c}\frac{\partial c}{\partial x_i} \tag{6}$$

The cost benefit factor κ_i of a design parameter x_i is now defined as:

$$\kappa_i = \frac{k_{0,p,i}}{k_{0,c,i}} = \left(\frac{x_i}{p}\frac{\partial p}{\partial x_i}\right)\left(\frac{x_i}{c}\frac{\partial c}{\partial x_i}\right)^{-1} = \frac{c}{p}\left(\frac{\partial p}{\partial x_i}\right)\left(\frac{\partial c}{\partial x_i}\right)^{-1} \tag{7}$$

A working definition used for technology critical is if the sum of all (n):

$$\kappa = \sum_{i=1}^{n} \kappa_i < 1 \tag{8}$$

κ is here called the criticality factor. A practical definition used for criticality can also be to just look at the design variable with the highest impact, since very often only one design parameter is very dominant:

$$\kappa < 1 \tag{9}$$

4.3 The concept of technology criticality

The technology comfort zone is the region where it is easy to select parameters, i.e., the region where the requirements can be met with a comfortable margin. In this region, it is not necessary to particularly optimize the product for performance. Instead, to get competitive product, other aspects need to be emphasized.

In the technology comfort zone, the performance is more or less, directly proportional to the design parameters. Here, this is defined when the cost benefit factor is more than half an order of magnitude larger than the critical, i.e., $\kappa > 3$ In the region in-between we say that the system is technology sensitive.

The assumption made here is that changing the size of a component to change its performance does not involve any development of the technology as such. For instance, increasing the size of a battery to gain capacity does not imply that the technology is advanced. However, if the energy density, which is the amount of energy that can be stored in a battery of a given size, can be boosted, this requires an improvement of the technology as such.

5. Application Example: Battery electric aircraft

To study the case of battery electric aircraft. Battery electric and fuel cell electric aircraft has been investigated e.g., in [3] and [4]. For a battery electric aircraft, the Breguet range equation for range, *R*, modified for battery powered aircraft can be expressed as:

$$R = \eta \frac{k_b}{g}\left(\frac{L}{D}\right)\frac{W_b}{W_0} \tag{10}$$

To Here $W_b$is the battery weight, $W_0$is the takeoff weight, (L/D) is the lift over drag at cruise, and c is the specific energy of the battery. η is the propulsive efficiency, k_b is the specific energy of the batteries. Note that k_b/g represents the altitude to which the battery could be lifted if all its energy was converted to potential energy. Introducing:

$$W_b = \phi W_0 \tag{11}$$

Furthermore, introducing the structure weight (empty weight with battery excluded):

$$W_b = \beta W_0 \tag{12}$$

So that the takeoff weight can be written as:

$$W_0 = W_s + W_b + W_{pay} \tag{13}$$

The payload can then be written as:

$$W_{pay} = (1 - \phi - \beta)W_0 \tag{14}$$

The performance is here defined as the range of the aircraft, i.e.

$$p = R \tag{15}$$

The cost (of transporting gods) is considered proportional to the takeoff weight divided by the payload. Hence:

$$c = W_0/W_{pay} = 1/(1 - \phi - \beta) \tag{16}$$

Using the battery fraction ϕ as the design variable the range can be written as:

$$R = \eta \frac{k_b}{g}\left(\frac{L}{D}\right)\phi \tag{17}$$

the normalized sensitivity to performance is:

$$k_{0,p} = \frac{x_i}{p}\frac{\partial p}{\partial x_i} = \frac{\phi}{R}\frac{\partial R}{\partial \phi} = \frac{\phi}{\eta\frac{k_b}{g}\left(\frac{L}{D}\right)\phi}\eta\frac{k_b}{g}\left(\frac{L}{D}\right) = 1 \tag{18}$$

The normalized sensitivity to cost is in the same way:

$$k_{0,c} = \frac{x_i}{c}\frac{\partial c}{\partial x_i} = \frac{\phi}{c}\frac{\partial\big(1/(1-\phi-\beta)\big)}{\partial x_i} = \frac{\phi}{1-\phi-\beta} \tag{19}$$

Hence

$$\kappa = \frac{k_{0,p}}{k_{0,c}} = \frac{1-\phi-\beta}{\phi} \tag{20}$$

Solving ϕ for range, κ can be expressed as a function of range, R.

$$R = \frac{\phi\eta(1-\beta)k_b(L/D)}{(\phi+1)g} \tag{21}$$

Here the following data are used. $\beta = 0.4$, $(L/D) = 20$, $\eta = 0.9$ and $g = 9.82\ [m/s^2]$. The battery specific energy k_{eb} is here assumed to evolve over time with an increase of 5% every year. This is of course very difficult to predict but looking at historical data it is not an unreasonable assumption. As a starting point a value of 200Wh/kg (720kJ) at pack level is assumed in 2022.

$$k_b = 720000 \times 1.05^{y-2022} \tag{22}$$

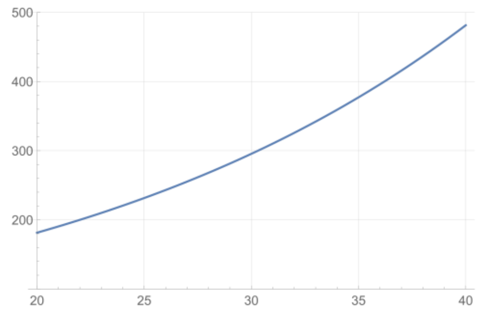

Figure 2. Assumed evolution of battery specific energy at pack level (in Wh) as a function of year.

Plotting κ for the year 2022, 2030 and 2040 yields the different requirement regions for the years.

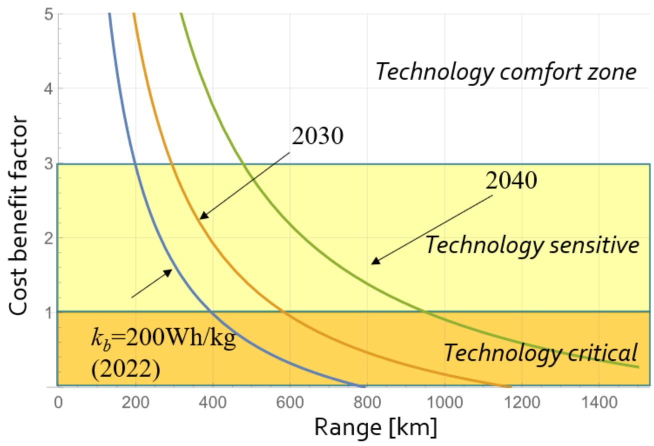

Figure 3. Cost benefit factor as a function of range for the years 2022, 2030 and 2040

The same approach can be used for hydrogen in pressurized tanks. With pressurized tanks the fuel it is hard to get a fraction of hydrogen over 6% in the tank since most of the weight will go to the tank itself. This means that the energy storage has an almost constant mass, much like a battery. With a specific energy at the tank level of 1980 Wh/kg and a fuel cell efficiency of 60% the following cost benefit factor is obtained:

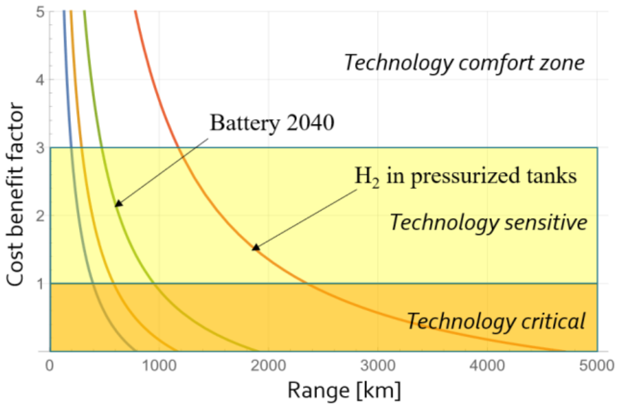

Figure 4. Cost benefit as a function of theoretical range including high pressure hydrogen

Cruise Speed

Another performance that is of interest is the cruise speed. The cruise speed is highly dependent on engine power, but power also drives weight which in turn increases drag. Therefore, the specific power of the power plant can become critical. It is interesting to look at the historical trend of some propeller aircraft. Looking at the fraction of the aircraft weight that is propulsion and specific power of the propulsion system, it is possible to establish a cost-benefit factor.

From first principles we have that the speed can be calculated as:

$$v = \frac{P\eta\,(L/D)}{g} \tag{23}$$

Here P is the propulsive power, η is the propulsive efficiency (L/D) is the lift over drag quotient. G is the gravitational constant. Furthermore, the power can be expressed as:

$$P = m_p k_p = \gamma m_0 k_p \tag{24}$$

Here k_p is the specific power of the propulsion system and γ is the mass fraction of propulsion on the aircraft. The performance variable p is set to v and the design variable is set to γ so that:

$$k_{0,p} = \frac{x_i}{p}\frac{\partial p}{\partial x_i} = \frac{\gamma}{v}\frac{\partial v}{\partial \gamma} = 1 \tag{25}$$

The cost function is set to be the quotient between take-off weight and load (to be distributed between energy storage and payload).

$$c = \frac{m_0}{m_{load}} \tag{26}$$

The maximum load can be calculated as:

$$m_{load} = m_0(1 - \psi - \gamma) \tag{27}$$

Hence:

$$c = \frac{1}{(1-\psi-\gamma)} \tag{28}$$

The normalized sensitivity of cost can then be calculated as:

$$k_{0,c} = \frac{x_i}{c}\frac{\partial c}{\partial x_i} = \frac{\gamma}{c}\frac{\partial\left(1/(1-\psi-\gamma)\right)}{\partial x_i} = \frac{\gamma}{1-\psi-\gamma} \tag{29}$$

And finally, the cost benefit factor:

$$\kappa = \frac{k_{0,p}}{k_{0,c}} = \frac{1-\psi-\gamma}{\gamma} \tag{30}$$

It can be noted that with the older aircraft the cost-benefit factor is just above 2 putting them into the technology sensitive or comfort zone. A higher propulsion mass fraction would mean sacrificing too much payload. The exception is the P-51 Mustang that was a high-performance fighter that put it into the technology critical zone. It is an indication that the engine technology was a critical technology. However, with the advent of turboprop engines the specific power increased substantially indicating that speed is limited by other aspects than power (i.e., compressibility effects on propellers), as indicated by the high values on the Saab 340 and the ATR72 turboprop aircraft.

Table 1. The cost benefit factor for various historic aircraft.

Aircraft	Prop fraction	Spec power	Struct fraction	kappa
Fokker Trimotor	0.18	880	0.44	2.12
Douglas DC3	0.12	1561	0.57	2.60
B-29	0.11	1322	0.53	3.27
P-51	0.20	1488	0.65	0.79
Saab 340	0.04	7020	0.63	9.31
ATR72	0.05	3846	0.54	7.76

This gives an indication of the size limits on a fuel cell aircraft to be viable. In the propulsion weight we here have to take into account both the fuel cell, the electric motor and other system components needed. If the electric motor has a sustained specific power of about 2kW/kg and a fuel cell has a similar power density including systems, that would give us a total of 1kW/kg which is on par with a piston engine in the thirties. This would most likely put us into the technology sensitive zone. However, as with then, we can probably expect a development in the same way as with the piston engine, such that a speed comparable to turboprops can be achieved.

6. Conclusion

In this paper it was demonstrated a systematic way to study the regions of viable requirements. It was here demonstrated on electric aircraft and also validated using historical data on aircraft where the cost-benefit factor shows to be a valid indicator. Furthermore, it is easy to combine with forecasting to see future potential areas for new products. In this way to establish the requirements that can be met at a certain time in the future. This was demonstrated on battery and fuel cell electric aircraft.

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8. Contact Author Email Address

luciana.pereira@ufabc.edu.br

9. Copyright Statement

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