

# A Consumer-Centric Methodology for Selecting Architectures against Multiple Objectives and Its Application to the In-Flight Catering and Entertainment System

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## Abstract

A new collaborative consumer-centric decision-making platform to support the design of innovative products is presented and applied to in-flight entertainment systems. Based on a six-step methodology, it allows designers to dynamically and exhaustively decompose their problem and generate all feasible concepts. Automatically removing unfeasible concepts decreases the overall execution time by a factor of  $10^3$ , while maintaining consistency and exhaustiveness. An automatically generated survey is combined with a quantitative multiple-objective option evaluation. This supports decision-making via rapid trade-off visualization and systematic rankings based on requirement prioritization. Finally, a robustness analysis allows designers to take into account requirements' uncertainty.

## 1. Introduction and motivation

Current economic conditions require designers to develop innovative products that perfectly meet customers' requirements. While multiple marketing approaches exist, one of the most commonly used for innovative products is the technology push strategy.<sup>1</sup> It is based on the design of new products due to enhancements in manufacturing techniques or technological capabilities. These changes result in an improvement of the products on the market, their cost and performance. While this strategy tends to favor innovation, it often fails to adequately capture customers' needs. A good example of a technology push failure is the Sinclair C5<sup>2</sup>: a small one-person electrically powered transport vehicle with pedal cycling assistance. This vehicle was developed in 1985 to be the first electric car. It was first launched in Great Britain and even though it was a state-of-the-art vehicle, it did not receive great reviews and sales never went high. The public found it inappropriate for the British market as the C5 was not rainproof, could not go faster than 24 km/h,<sup>3</sup> and needed pedaling for hill climbing. Hence, even though the chassis was designed by Lotus Cars and the material used was extremely innovative for 1985, the technology push strategy failed. Another good example of a technology push failure is the Concorde: a supersonic aircraft based on state-of-the-art technologies. While it benefited from great performance, cost considerations were not taken into account during the design. A ticket costed over \$6,000 in 1980<sup>4</sup> (around \$18,000 in 2015) for a round trip between London and Washington. As a result, only few passengers could afford such a price. The Concorde was mainly used by companies paying the trip for their employees, not so much by the general public. Thus, not enough passengers flew the Concorde to make it profitable enough, which led to the cancellation of the program. To avoid such failures, another approach can be used: the market pull strategy. It is based on a clear and identified customer demand. This approach usually aims at generating a response to marketing actions. However, this approach fails to support the development of breakthrough products. As such, there is a need for an approach that both favors innovative products and accounts for the voice of the customer.

According to Schrage,<sup>5</sup> 37% of project failures or delays are related to requirement definition problems: 13% come from poor user input, 12% from incomplete requirements, and 12% from changes in requirements. Therefore, requirements analysis is the key factor to start a project and to ensure its completion and sustainability. Suh<sup>5</sup> affirmed that "the ability to define the problem is the most important and difficult task in engineering". Moreover, companies cannot afford to launch a product that will not meet customers' expectations. According to the Harvard Business Review,<sup>6</sup> about 75% of packaged goods are considered as failures, as they fail to earn more than \$7.5 million the first year. Due to the increase in competition, firms have to develop innovative products that successfully attract customers and meet both design and marketing requirements. Indeed, in addition to typical design requirements such

as feasibility, extra requirements pile up when the product moves along its life-cycle. As a consequence, the number of design objectives tends to increase, leading to more complex decisions.

In the aviation industry, expectations differ between passengers, airlines, and manufacturers resulting in products that do not entirely meet the needs of the end-users: the passengers. In particular, the Association for Passenger Experience<sup>7</sup> (APEX) conducted a survey and discovered that the main concern for passengers is the in-flight entertainment (IFE) and that it should be the first axis of improvement in future aircraft designs. In the meantime, airlines are transforming in-flight experience by removing the TV-screens and asking passengers to plug in their own tablet or computer and then to pay for TV access.<sup>8</sup> Even if this would enhance the flight experience, not all passengers own a tablet or want to pay for this new system. As a consequence, this solution does not add value in comparison to the standard one. For this research, the in-flight experience systems will be used as a proof of concept. As passenger traffic is rapidly expanding and outperforming the world GDP growth, the number of aircraft in service is expected to double over the next 20 years.<sup>9</sup> Therefore, in addition to the traditional metrics of interest such as fuel consumption, noise or emissions, airlines and manufacturers are now looking at other aspects such as passenger experience. In June 2014, the APEX conducted a survey to understand passengers' behavior during the flight and their wishes.<sup>7</sup> They found out that during a flight, people spend most of their time using the in-flight entertainment systems and personal devices to watch movies (24% of the time), to play (11%), and to go on social networks (6%). Nowadays, more than fifty airlines provide either onboard Wi-Fi or GSM access. According to the APEX, in-flight connectivity is considered by passengers as being the number one area for improvement. Since 2013, phone use is not banned anymore in the aircraft so passengers want to be able to use their phones and stay connected during the entire flight. Moreover, Airbus equipped all their new aircraft with onboard Wi-Fi systems that are not used yet.<sup>10</sup> Hence, a better connectivity between passengers' electronic devices and provided screens could be implemented. A digitization of all in-flight magazines and newspapers would also help airlines reduce both weight and cost. While today flight attendants are dependent on the use of the call button, a new on-demand entertainment system would allow them to receive passengers' orders from the galley and improve passengers' connectivity by letting them connect their personal device or access a broader offer of IFE. There are many other functions that can be developed with numerous alternative solutions. Thus, there is a need for airlines to select the best architecture balancing customers' expectations and performance metrics such as cost, weight, etc.

This paper aims at developing a new methodology that incorporates consumers' preferences to support a systematic and robust concept selection. This method can potentially be applied to all design problems, especially when seeking innovative solutions. For that purpose, a review of the current design methods is first performed to evaluate, compare, and leverage existing techniques. Then, the proposed methodology is presented along with its application to the IFE system, and its implementation into a new collaborative platform. Finally, the developed capabilities are summarized and recommendations are provided for the design of IFE systems.

## 2. Review of previous work

To identify the best solution to a given problem, designers traditionally rely on their own experience. However, for the design of revolutionary concepts, experience is not reliable as no historical data is available. Moreover, the reliance on experience does not allow a large number of innovative solutions to come out of the process. To address these shortcomings, systems engineering methods have been developed based on the traditional Vee-diagram<sup>11</sup> approach. It divides the project development into two main phases. First, it starts with the requirements identification, then a decomposition of the system is performed to end with the selection of the best concept. The second phase consists in the system re-composition and requirements validation. According to Mavris,<sup>12</sup> a large part of the design cost is committed at the beginning of the process as major decisions are made. Moreover, once the design enters the re-composition phase, the architecture is fixed so no changes can be made. Hence, requirements identification and system definition are the main focus of this research. For that purpose, a generic Top-Down Design Decision Support Process<sup>13</sup> detailed in Fig. 1 is followed. Its six steps can be grouped into two phases discussed in this section: to capture customers' requirements and to propagate the requirements.

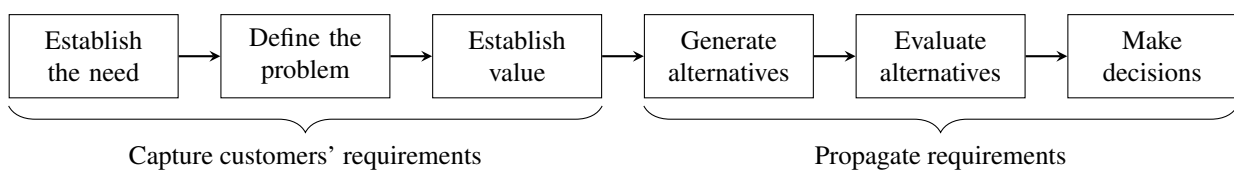


Figure 1: Top-Down Design Decision Support Process

## 2.1 Capture customers' requirements

Different types of requirement classifications exist: Saxena et al.<sup>14</sup> separate product and process requirements. The method developed by Pinon-Fischer et al.,<sup>15</sup> used at the Aerospace Systems Design Laboratory (ASDL) of the Georgia Institute of Technology, classifies the requirements into four categories: regulations, customer requirements, standards, and internal requirements. This method enables the modification of requirements and the tracking of their origin and importance for later use in the design process. Pandey<sup>16</sup> suggests a four-phase model to get clear, consistent, modifiable, and traceable requirements. Starting with requirements elicitation and development, requirements are then documented, validated and verified, to end with requirements management and planning.

For any model previously cited, requirements definition leads to customer-related problems as it is difficult to understand the real expectations and preferences of customers with respect to a novel concept. Indeed, when asked about a specific topic, consumers tend to elaborate and put words on ideas, which do not reflect their original train of thoughts.<sup>17</sup> As researchers tend to be biased by their experience, there is a risk that no innovative product may come out of the design process.<sup>18</sup> Therefore, there is a need for a model that would allow constant interaction with customers to clearly define their needs throughout the whole requirements definition process.

Companies used to rely on the brilliance of tastemakers to determine customers' needs as feelings were the key of market forecasting.<sup>19</sup> Nowadays, with the increase in technology and data access, market forecasting is going beyond simple expert analysis. Tools to predict and shape consumers' preferences have existed for many years but only with the expansion of new technologies have they become more widely used. In the early 1940s, the Bureau of Applied Research at Columbia University<sup>20</sup> developed the Lazarsfeld-Stanton Program Analyzer. It required a sample of consumers to record their feeling about the product when looking at it. From that data, trends were identified and prediction models created. Technology is becoming a key enabler of predictive tools as more data can be generated on consumer behaviors and preferences via the Internet. Several tools exist to predict both consumer preferences and product success. Platinum Blue Music Intelligence<sup>21</sup> uses "spectral deconvolution" of sound waves to identify songs that would be appealing to a certain category of customers. Epagogix<sup>21</sup> uses a proprietary expert system with neural network-based algorithms to predict a movie's success even before its shooting. Many movie studios also use regression analysis to project the success of a film before its release. It was demonstrated that predicting the success of a product was one of the hardest tasks so marketers focused more on the consumer recommendation aspect. In particular, Amazon was one of the pioneers in the use of collaborative filtering in the late 1990s.<sup>21</sup> Collaborative filtering consists in creating patterns of consumption to give shopping recommendations. However, the method has many limitations: it cannot determine if the product was bought for the consumer's personal use or for someone else, and it does not allow to confidently predict the products consumers will buy next and the reasons they like this product. Surveys are often used in collaboration with social networks<sup>21,22</sup> to identify the degree of acceptance or satisfaction. For example, after buying a product on Amazon, customers usually receive an e-mail asking to grade the product and give a review. Similarly, airlines randomly select a small amount of passengers to be surveyed. With the data retrieved, firms can improve on the service/product they offer. However, customer satisfaction surveys are rather used to increase customer loyalty than to get information on the improvements to be performed. Indeed, customers are reminded of the brand after their sales when they answer the survey so they elaborate more about it and remember the brand longer.<sup>23</sup> With this approach, companies always administer the survey after the product is commercialized. If the product is not accepted by customers, it tends to be removed from the market. Thus, all the costs incurred become useless and the design process has to start over, leading to higher costs.<sup>12</sup> Hence, there is a need to ask for customers' opinions earlier in the design process and to include them all along the process to decrease cost of change, to improve products, and to have solutions that better fit their expectations.

## 2.2 Propagate customers' requirements

Once requirements have been defined, they must be propagated to define the system. Many methodologies exist to enable a systematic and rigorous generation of alternatives based on the list of requirements. Some of the most common environments are described below.

Dassault Systems developed an integrated platform: the Requirements, Functional, Logical and Physical Design (RFLP) approach.<sup>24</sup> It is a model-based approach for the application of systems engineering to virtual design and validation. It allows activities between different teams to be separated, design to be coordinated, knowledge to be shared, and program cycle times to be reduced. Even though this approach enables a better communication between the different stakeholders, it does not allow requirements to be propagated to generate alternatives. It only serves as a support and management tool rather than being a design tool.

The ASDL<sup>25</sup> developed a dynamic and integrated method that allows easy decomposition and understanding of the complex problem: the Interactive Reconfigurable Matrix of Alternatives (IRMA). This method shrinks the design

space and documents the decision-making process by keeping track of down-selections. It is based on a set of filters that eliminate options based on their incompatibilities. At the end of the process, only one family of concepts is presented to designers. Even though this method supports rapid alternative generation, it cannot be used to further analyze the concept family. Other tools need to be implemented to select the best solution with respect to a specific set of requirements.

Even though the IRMA greatly supports the generation of design concepts, it is based on a static functional decomposition. To overcome this shortcoming, the Adaptive Reconfigurable Matrix of Alternatives<sup>26</sup> (ARM) that relies on functional induction, has been developed. It acts as a hybrid of the IRMA and the function/means tree so that both functional and physical breakdown scan be interactively managed. While being more flexible than the IRMA, it suffers from the same main pitfall: design variables are not tracked. In addition, this tool aims at supporting the designers in the concept selection rather than in the concept generation,<sup>27</sup> and it does not provide an exhaustive exploration of the design space.

The Quality Function Deployment<sup>5</sup> method (QFD), implemented as the House of Quality (Fig. 2), creates the link between the customers' voice and the engineering characteristics, which are quantifiable measures of the requirements. It relies on multiple matrices that describe the associations between the point of view of the customer, the product features, the different manufacturing processes, and the support characteristics. It aims at identifying the main parameters based on importance factors given by customers and at studying the effect of product design on downstream processes. Each matrix used in the QFD answers two questions: What issues are there? How to solve those issues? The interior elements of the matrices relate the Whats to the Hows and give the importance of the latter by summing up the relationships. This enables the identification of the most important characteristics to help decision makers. This importance is modeled by numbers and charts but those are not the end, they are just a mean to identify main characteristics of the concept.

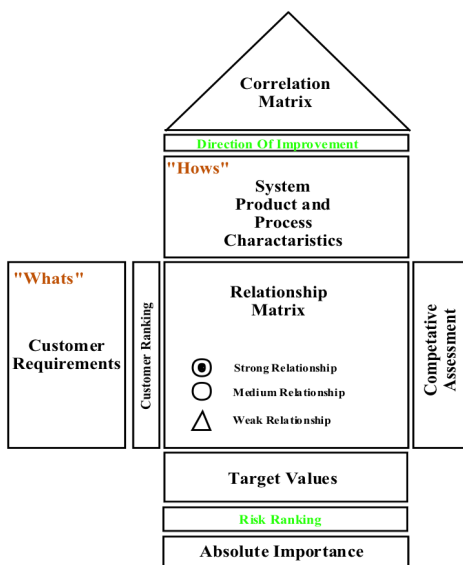


Figure 2: House of Quality

The matrices are decomposed as following: the Whats correspond to the customers' requirements and are listed on the left-hand side of the matrix. The Hows correspond to ways of answering or measuring the Whats and are listed on the top of the main matrix. The latter represents the relationship matrix; it gives the degree of linkage between the Whats and the Hows. The importance of the Whats (requirements) is calculated using customer rankings. It is then multiplied by the level of relationship (weak, medium or strong) to rank the Whats. The "roof" of the House of Quality is made of the correlation matrix. It measures the interrelationships between different Hows and can provide trade-off information. Competitive assessment, direction of improvement, and risk/difficulty matrices can be added on the sides. However, the QFD sometimes leads to misinterpretations and to a product that does not answer market needs and does not entirely reflect the voice of the customer.

To conclude, there is no methodology that enables both to keep the customer involved in the design process and to provide a collaborative decision-making platform when designing innovative products. This gap will be bridged in the next section, with the development of a new methodology.

### 3. Proposed methodology

As discussed in Section 1, this paper aims at providing a collaborative decision-making platform to support the design of innovative products. Section 2 identified several pitfalls in current approaches that prevent meeting this research objective. To address these shortcomings, a new methodology is developed. First, a dynamic functional decomposition helps designers identify the required functions. These functions are then used to generate feasible design alternatives based on options for each identified functions. Each of these options are graded and importance factors are assigned to functions and design objectives. To account for consumer preferences, a survey specific to the problem is automatically generated. Next, a multi-objective decision-making interface allows designers both to perform trade-offs and to find the

best concept(s). Finally, the robustness of the selected solution to changes in requirements can be verified. Inspired by the QFD, Fig. 3 illustrates the different steps of this new methodology. These steps are further detailed in this section along with their implementation into an integrated environment called Architecture Selection based on Consumer Expectations and Needs to support Decision-making (ASCEND).

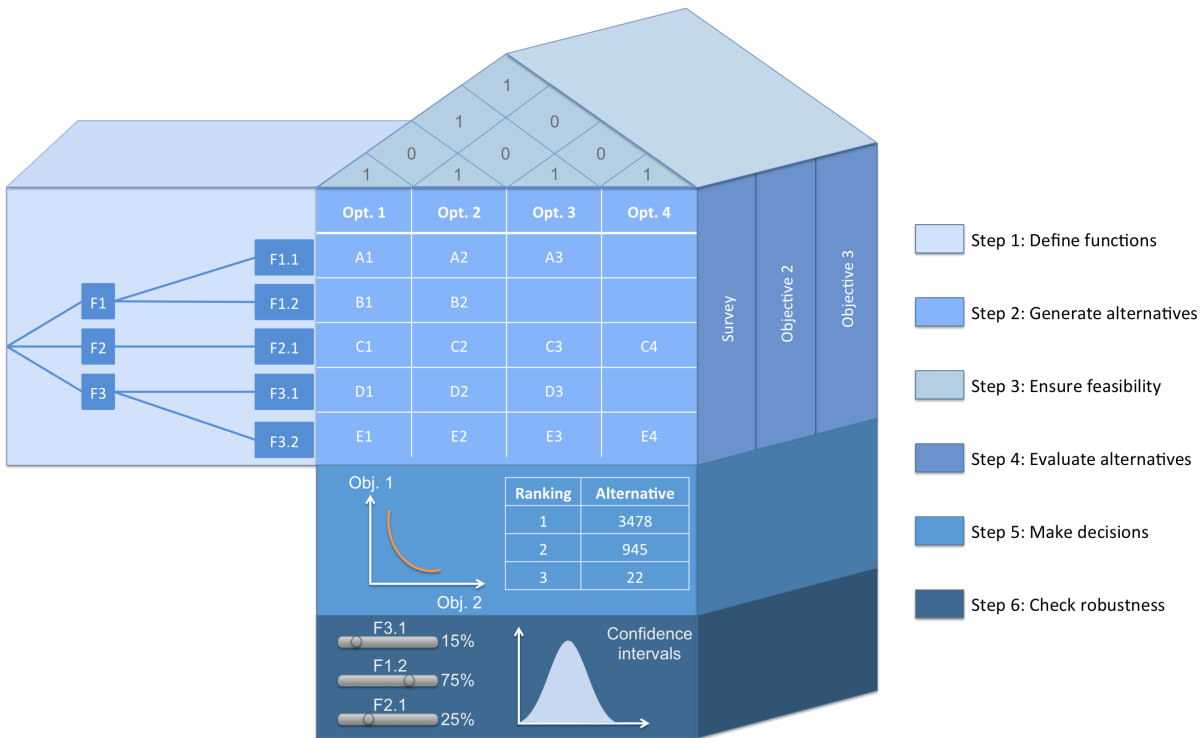


Figure 3: Modified QFD

### 3.1 Step 1: Define functions

Customer requirements are rarely expressed in “engineering” terms. Therefore, there is a need for a technique that transforms these requirements into a clear and quantitative version of the problem. For that purpose, a functional analysis is implemented similar to the one used in traditional and commonly used software such as Catia V6,<sup>28</sup> DOORS,<sup>29</sup> Oracle Agile,<sup>30</sup> Autodesk PLM 360,<sup>30</sup> and Core concept.<sup>31</sup>

A functional analysis progressively breaks down complex systems into more detailed functions that can be easily treated.<sup>32</sup> Therefore, it allows designers to identify all functions required to meet the overall requirements, while also helping them identify hidden functions. The overall traceability is also improved by relating functions to requirements. A functional decomposition starts with the definition of the system in a functional language and then decomposes the top-level functions into sub-functions. High-level performance requirements are then transformed into detailed functions, performance criteria, or design constraints. In parallel, internal and external functional interfaces need to be defined to enable functional partitioning. The latter consists in grouping functions that logically fit with the components likely to be used, and to minimize functional interfaces.

To help designers visualize this decomposition, a dynamic tree diagram is implemented. Each branch can be collapsed and moved by a simple dragging. Nodes can be easily added, edited, and deleted. Users can load an existing project and save their modifications. For IFE systems, a review of existing systems<sup>10,33–35</sup> was performed and the tree was created using ASCEND, as displayed in Fig. 4. Once the decomposition has been performed by designers, an algorithm automatically identifies the last nodes of the tree corresponding to the required functions of the system. The processing of these functions is discussed in the next step.

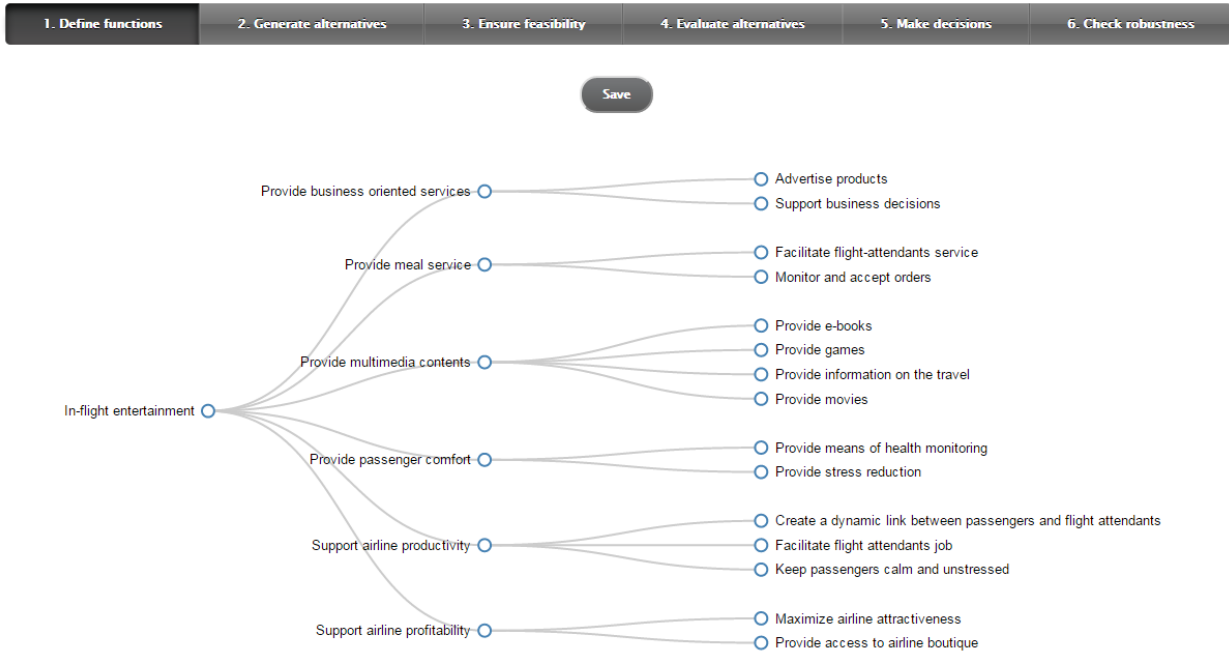


Figure 4: Functional decomposition of the IFE system

### 3.2 Step 2: Generate alternatives

This step aims at generating all possible alternatives that could fulfill the previously identified functions. Existing methodologies include decision trees,<sup>36</sup> design catalogs,<sup>37</sup> the Theory of Inventive Problem Solving<sup>38</sup> (TRIZ), and the morphological analysis.<sup>39</sup> Design catalogs require designers to select a handful of representative solutions based on their experience. This method is thus not suitable for revolutionary concepts as only a small portion of the design space is investigated. The TRIZ relies on the exploration of past solutions and is composed of 5 steps: identify the problem, formulate the problem by identifying potential gaps or technical difficulties, search for previously well solved problems, identify analogous solved problems, and adapt the identified solutions to the stated problem. However it does not work for innovative problems and it is not a systematic method to generate concepts. Decision trees consist in the generation of all the possible paths to be followed to achieve a specific goal. If goals correspond to the system features then the tree helps laying out the different alternatives. Even though this method is systematic and generates only feasible solutions, it requires to individually generate each alternative and might lead to missing alternatives. Finally, the morphological analysis is a methodology to explore all possible solutions for multi-dimensional and non-quantifiable complex problems. It is a rigorous and systematic full-factorial approach of the design space definition that also generates non-feasible combinations.

Based on the previous study, the morphological analysis is selected for its capability to systematically and rigorously generate all possible combinations of options based on a functional decomposition. This method is notably successful for multi-dimensional problems and provides a functional, intelligent, and structured approach to generate alternatives.<sup>27</sup> Moreover, it enables a complete exploration of the design space and favors innovation as it generates the maximum number of possible combinations. A morphological analysis is usually implemented using a morphological matrix, also called matrix of alternatives. The latter is a two-dimensional matrix that represents the system: each row corresponds to a function/feature and each column corresponds to an option. If the morphological matrix  $M$  is defined by its rows  $i$  and its columns  $j$ , the number of generated alternatives can be calculated using Eq. 1.

$$N_{alt} = \prod_i \left( \sum_j M_{i,j}^* \right) \quad \text{where} \quad \begin{cases} M_{i,j}^* = 1 & \text{if } M_{i,j} \neq \emptyset \\ M_{i,j}^* = 0 & \text{if } M_{i,j} = \emptyset \end{cases} \quad (1)$$

The implementation of this step in ASCEND is presented in Fig. 5. The morphological analysis has two main drawbacks: it generates too many and unfeasible alternatives. Indeed, based on 42 options distributed among 15 functions, the morphological matrix generates 2,985,984 possible combinations. This shows the exhaustiveness of the

proposed methodology. The next step aims at ensuring the feasibility of each concept by addressing compatibility issues between options.

1. Define functions	2. Generate alternatives	3. Ensure feasibility	4. Evaluate alternatives	5. Make decisions	6. Check robustness
2,985,984 possible combinations					
	Option 1	Option 2	Option 3	Option 4	
Advertise products	Pop-ups	Advertising before launching a movie	Online catalogs		
Support business decisions	Survey the aircraft	Ground communications			
Facilitate flight-attendants service	Automatize orders	Alert passengers of meal arrival	Monitor inventory		
Monitor and accept orders	On-screen selection	Voice			
Provide e-books	Free on-screen application	Free e-reader	Link with personal device	Paid application	
Provide games	Application	Paper	Flight attendant		
Provide information on the travel	Free on-screen application	Free tablet	Link with personal device	Paid application	
Provide movies	Free on-screen application	Free gaming tablet	Link with personal device	Paid application	
Provide means of health monitoring	Sensors embedded in seats	External sensors			
Provide stress reduction	Video guided stress-reduction exercises	Digital entertainment			
Create a dynamic link between passengers and flight attendants	Application	Voice	Button		
Facilitate flight attendants job	Digital aid for aviation safety videos and calls	Voice	Button		
Keep passengers calm and unstressed	Digital entertainment	Video guided relaxation techniques			
Maximize airline attractiveness	Variety of free choices	Increased seat comfort			
Provide access to airline boutique	Internet access	Restricted access	Airline website restricted access		

Figure 5: Morphological matrix for the IFE system

### 3.3 Step 3: Ensure feasibility

Unfeasible alternatives are useless to analyze and represent a waste of time for designers. In addition, they increase the size of the design space without valuable gains. Thus, it becomes crucial to ensure the feasibility of the generated concepts using a compatibility matrix  $C$ . This matrix<sup>27</sup> is symmetric so that only the upper (or lower) triangular needs to be completed by either 0 or 1 according to the rule presented in Eq. 2. In this equation,  $k$  and  $l$  represent the  $k^{\text{th}}$  row and the  $l^{\text{th}}$  column of the matrix.

$$C_{k,l} = \begin{cases} 1 & \text{if options } k \text{ and } l \text{ are compatible} \\ 0 & \text{if options } k \text{ and } l \text{ are incompatible} \end{cases} \quad (2)$$

Using the definition of the compatibility matrix, the diagonal can be prefilled by ones since a given option is necessarily compatible with itself. In addition, while functions can be described by different options, only one option per function can be selected for a given design alternative. As a consequence, all options used to define the same function are necessarily incompatible. Therefore, additional entries can be prefilled. As a consequence, the final number of entries that must be filled by the designer is reduced to  $N_f$ , as defined in Eq. 3.

$$N_f = \frac{N_{alt}(N_{alt} - 1)}{2} - \sum_i \frac{(\sum_j M_{i,j}^*)((\sum_j M_{i,j}^*) - 1)}{2} \quad (3)$$

The implementation of this step in ASCEND has reduced the number of alternatives to be investigated to 6,654 feasible solutions. Hence, with only 67 incompatible couples of options (or inputs from users), the number of alternatives that must be investigated is reduced by a factor of  $10^3$ . In other words, each input from the designer results in the removal of around 45,000 non-feasible concepts. However, the number of alternatives to be considered is still too large. As a consequence, the next step aims at evaluating them so that only the most promising are investigated.

### 3.4 Step 4: Evaluate alternatives

To select the best system, the different feasible alternatives need to be compared and evaluated with respect to multiple design objectives. To enable this comparison, quantitative information need to be infused in the decision process. The main difficulty is to combine metrics that cannot be naturally compared and that do not have the same orders of magnitude such as safety, weight, size, and comfort. For that purpose, an Overall Evaluation Criterion (OEC)<sup>5,40</sup> is implemented in ASCEND. The OEC is a value function that aggregates multiple attributes. Its general formulation, presented in Eq. 4, evaluates the performance of an alternative against the  $j^{\text{th}}$  objective  $y_j$ , where  $y_j$  is the function

to minimize and  $x_k$  the grade assigned to the option selected to fulfill the  $k^{\text{th}}$  function of the studied alternative. The weighing factor  $f_k$  represents the importance of the  $k^{\text{th}}$  function compared to the others.  $x_T$  is the normalized target value of the selected function and  $\mu$  corresponds to a switch factor. If the aim is to maximize the objective, then  $\mu = -1$  to maintain a minimizing direction of improvement. Similarly,  $\mu = 1$  or  $\mu = 2$  if the aim is to minimize the objective or to hit a target, respectively.

$$y_j = \frac{\mu}{|\mu| \sum_k f_k} \sum_k f_k (x_{i,k} - (|\mu| - 1) x_{T,k}) \quad (4)$$

To grade each option, a quantitative mapping between options and each design objective is developed by replacing all options in the morphological matrix by their grades. Hence, for each objective, a new layer is added in the modified QFD. The grade  $x_k$  assigned to the selected option of the alternative is calculated in three different manners, depending on its origin: using the consumer's point of view, computer-based models (CFD, FEM, etc.) or designers' experience. The customer point of view is retrieved via an automatically generated survey that designers can send to potential customers. By adding the generation and use of a consumer-centric survey, it is ensured that customers' requirements are validated throughout the entire design process. Indeed, customers are able to judge the different options. The questions are formulated as follows: "How interested are you in Option A to be implemented?" Customers have five possible answers that map to a normalized numerical scale: very interested (10), somewhat interested (5), neither interested nor uninterested (0), not very interested (-5), and not interested at all (-10). The average of all grades assigned by customers is then calculated for each option and entered in the relationship matrix. This represents the first layer of the modified QFD. If grades are assigned using another technique, a normalization of the values inputted on a real scale (kg, m, etc.) is automatically performed based on the range of values entered. This ensures consistency in the evaluation. For a given function, the normalization formula is presented in Eq. 5, where  $X_{i,k}$  is the grade assigned to the  $i^{\text{th}}$  option of the  $k^{\text{th}}$  function,  $X_{k,\min}$  ( $X_{k,\max}$ ) the minimum (maximum) grade of the options of the  $k^{\text{th}}$  function, and  $x_{i,k}$  the normalized grade of the  $i^{\text{th}}$  option of the  $k^{\text{th}}$  function. As such, after normalization, the new range is the same as the one for consumer-based grades:  $[-10; 10]$ .

$$x_{i,k} = 20 \frac{(X_{i,k} - X_{k,\min})}{(X_{k,\max} - X_{k,\min})} - 10 \quad (5)$$

Designers can also assign weighting factors to prioritize some functions with respect to others. This prevents a function with five sub-functions from becoming more important than one with only two sub-functions. Those weights  $f_k$  are assigned via slider bars and are automatically normalized by the algorithm.

For the IFE, three design objectives are defined: weight, passenger comfort, and implementation costs. Passenger comfort corresponds to the voice of the customers. A survey targeted to passengers was generated and reached 320 passengers who were mostly frequent flyers, from all origins, and all ages. Positive values correspond to a feeling that the option improves passenger comfort and negative values that it impinges on comfort. For implementation cost and weight, a literature review on existing systems was performed and the real values added to the corresponding relationship matrices. In particular, if weight is reduced, then the corresponding value is negative. For example, providing in-flight Wi-Fi with the 2Ku solution proposed by Gogo<sup>35</sup> leads to an added weight of 206 kg and an implementation cost of \$100,000.<sup>41</sup> The function weights have been defined after a prioritization of the different functions. For example, in order to sell the product, designers must create return on investment for the airline. Maximizing airline attractiveness is thus in the top functions so its weighting factor is one of the largest. However, providing stress reduction appears to be a secondary function so its weighting factor is smaller.

While, this step provides all the information required to evaluate and compare alternatives, there is still a need for lumping together all the data to support complex decisions. This is addressed in the next section.

### 3.5 Step 5: Make decisions

As systems become more complex and as the number of stakeholders tends to increase, the number of design objectives increases so that traditional single-objective selection processes usually fail. In addition, designers' experience and instincts face important limitations when dealing with innovative concepts. Thus, multi-objective decision-making techniques are required to systematically select the best solution(s). To successfully support decision makers, the proposed methodology must both handle dynamic requirements by capturing changes in design priorities, and allow designers to perform rapid trade-off analyses and identify new trends. To provide these capabilities, a combination of two methods is developed in ASCEND: a visual trade-off analysis and a dynamic prioritization tool.

### 3.5.1 Trade-off visualization

The goal of this section is to provide a method that can compare the generated alternatives against multiple objectives. Since the relative importance of each objective is not always clearly defined, multi-objective optimization methods must be used.

A first approach when dealing with multiple objectives is to combine them into a single aggregate function using weights to emphasize some of the objectives.<sup>42</sup> While being fast and easy to implement, this approach called compromise programming is very subjective because it depends on the definition of weighting factors. In addition, due to the lack of known prioritization and required capabilities to visualize trends, aggregation of the multiple objectives into a single objective function is not possible.

Instead of seeking for one optimum solution, another approach consists in generating a set of optimum solutions. For that purpose, the Pareto optimization is based on a partial ordering space instead of a total ordering space. This space has the following rules<sup>43</sup>: A “weakly dominates” B if A is better in some attributes and equal in others, C “strongly dominates” B if C is better in all attributes, A and C are “incomparable” if A is better than C in some attributes but worse in others. Based on these rules, the subset of all non-dominated points is called the Pareto frontier. Even though this technique does not provide a single optimized point, the visualization of the Pareto frontier allows decision-makers to better understand trade-offs that must be made. Another important advantage of this approach is its applicability to sub-problem optimization with its capability to only keep non-dominated alternatives without any decisions.

The goal of this new model is to allow designers to perform rapid trade-off analyses and identify new trends while minimizing designers’ bias so compromise programming cannot be used as it is too much sensitive to weighting factors. Therefore, a Pareto optimization is used for its capabilities to visualize trade-offs and simultaneously consider multiple objectives. Its implementation into ASCEND is presented in Fig. 6. The slider bars represent the weights assigned to each function. For the IFE, fifteen functions are kept and each has a certain percentage value that represent its importance. The percent importance is then normalized to ensure consistency in comparisons. Once weights for each function have been set, designers can choose which objectives to plot. Here implementation cost and weight are plotted. Finally, two types of points are plotted in the Pareto graph: dominated points are in light blue and non-dominated points are in darker blue. Even though some of the non-dominated points are inside the cloud, they may be dominated for those two objectives but are non-dominated when all objectives are taken into account. For these points, improving on one objective results in a deterioration in, at least, one other objective. Moreover, by passing the mouse over points, the corresponding architecture along with its options is displayed for faster identification. As such, designers can perform trade-off analyses and visualize the impact of their decisions on the various objectives. Nevertheless, Pareto optimization fails to identify the best concept meeting a specific set of requirements. The next section addresses this gap.

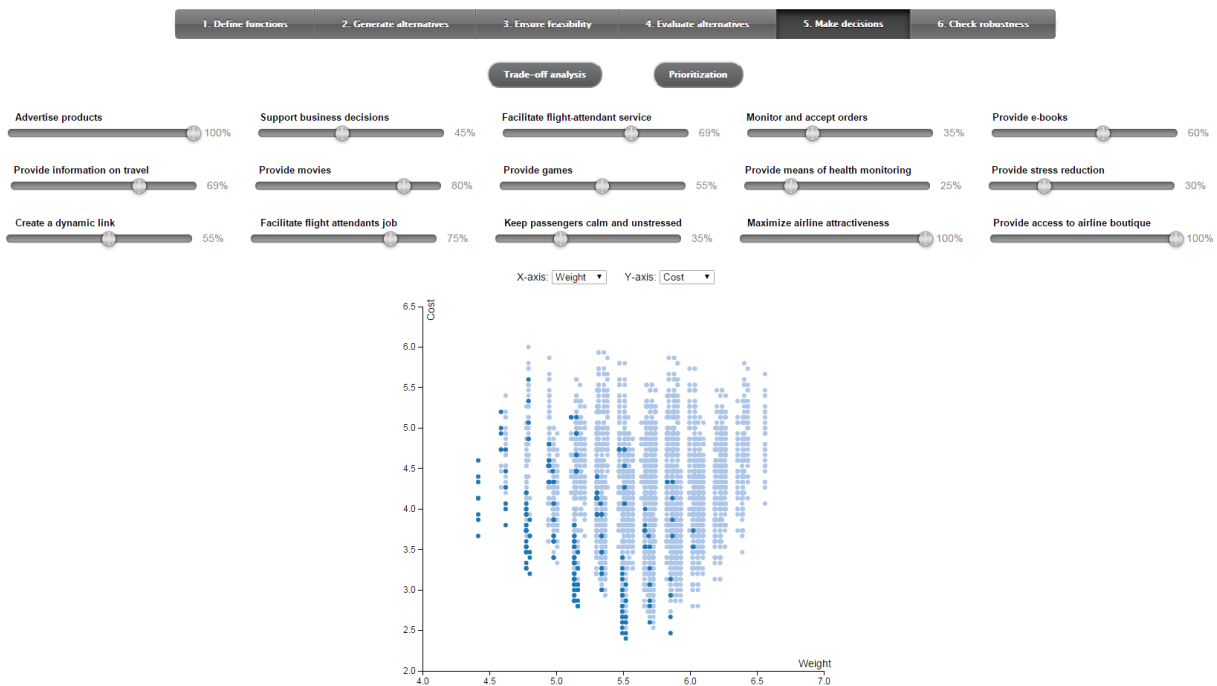


Figure 6: Pareto analysis

### 3.5.2 Prioritization

The aim of this methodology is not only to provide rapid trade-off analysis capabilities but also to enable a systematic and rigorous selection of the best concept with respect to different objectives. Therefore, Multi-Attribute Decision Making (MADM) techniques must be used to rank the different concepts according to the stated criteria. As a large number of techniques exist, only the ones focusing on cardinal information are reviewed. Indeed, those approaches are less subjective and more representative of the reality. The Pugh decision matrix<sup>44</sup> quantitatively compares multiple design alternatives. It leads to the best alternative with respect to an established set of design criteria (a baseline). This technique is able to simply handle numerous concepts but an unwise choice of baseline can lead to a non-optimum solution. The Elimination and Choice Translating Reality<sup>45</sup> (ELECTRE) technique is a method that dichotomizes alternatives based on outranking relationships. It is based on binary comparisons between two alternatives. One of the main drawbacks is the lack of ranking among the core alternatives. Consequently, there is no indication about “the best” solution. The Analytical Hierarchy Process<sup>46</sup> (AHP) tries to structure expert judgments to make rational decisions. This approach only requires comparisons between alternatives’ attributes. This method is powerful and flexible since it reduces highly complex decisions to simple one-on-one comparisons and can handle both qualitative and quantitative information. However, some inconsistencies could occur as each alternative is compared with all others. The Technique for Order of Preference by Similarity to Ideal Solution<sup>47</sup> (TOPSIS) is based on the assumption that the best alternative has the shortest distance to the utopia solution. The TOPSIS can compare a large number of criteria/concepts, is simple to implement, uses absolute values instead of a relative comparison to a baseline, and allows decision makers to orientate their preferences. However, solutions can be biased as it is very sensitive to weight attribution. Based on this comparison, the TOPSIS is selected for its capabilities to quantitatively and independently evaluate all concepts.

The TOPSIS<sup>47</sup> ranks alternatives based on their Euclidean distance to the utopia solution. The ranking of all alternatives is then obtained: from the best (closest to the utopia point) to the worst (farthest from the utopia point). The distance is computed using a utility function, as presented in Eq. 6 for each concept. The weighting factor  $w_i$  represents the importance of the  $i^{\text{th}}$  design objective, while  $y_i$  represents the grade of the studied alternative with respect to the  $i^{\text{th}}$  objective, as discussed in Section 3.4. They can all be dynamically assigned by the designer via slider bars in the proposed environment. As all values entered in the TOPSIS are already normalized, consistent results are ensured while comparing small and large numbers.

$$U(y) = \sum_i y_i w_i \quad (6)$$

This technique allows designers to develop multiple scenarios by changing both the importance of each function of the system and priorities among design objectives.

ASCEND only considers non-dominated concepts when calling the TOPSIS. As a consequence, none of these concepts can be improved on one objective without deteriorating at least one other. This increases even more the efficiency of the process by removing dominated points from the final list of alternatives. Indeed, for the IFE system, only 288 non-dominated points exist for the given combination of functions and objective weights. Therefore, the number of alternatives studied has been divided by more than 30. While this prioritization helps designers identify the best concept(s), it requires them to input design priorities and weighting factors, which are usually subjective and uncertain. The next section proposes a methodology to account for this uncertainty in requirements.

### 3.6 Step 6: Check robustness

Even though slider bars allow decision makers to easily change their design priorities, there still exists a large amount of uncertainty in design requirements. Moreover, there may be large discrepancies between customers’ and designers’ point of views. Requirements might also rapidly change over time, as new competitors or new technologies emerge. In particular, for IFE systems, avionic regulations have seen significant revolutions during the last two decades with the shift from a single overhead projector to a personalized screen and to the use of connected tablets. This change is mainly due to the suppression of the ban on the use of personal devices on board. In the past, all on-board devices had to be certified by the FAA and then by the different regulatory agencies of the countries where the aircraft may fly. The spread of cellphones and tablets as well as the increasing demand for in-flight connectivity led regulatory agencies to re-evaluate their positions. In addition, improvements in aircraft avionic systems meant that the use of personal devices on board was no longer a threat to aircraft safety.<sup>48</sup> When developing new concepts, designers cannot forecast all possible changes so the design process must be robust to those changes and ensure that the selected system provides a solution for most probable future scenarios.

In addition, to establish customers’ requirements, only a sample of the population is surveyed. However, there is no certainty that this sample accurately represents the final customers. The best design should not only positively

impact a small part of the population but also satisfy as much customers as possible. Thus, a trade-off between being the optimum with respect to performance and being the most robust to changes in requirements or to the widening of the target market has to be performed. For the IFE system, economy and business passengers do not expect the same level of service but to keep low costs, airlines would only change the casing and keep the same software. Finally, the product application may also change. For the IFE, many airlines exist and all do not have the same standards: between EasyJet and Emirates standards and consequently requirements vary. Within the same airline, different aircraft built by different manufacturers for different missions are operated. As such, when developing a product, designers should consider both variations in applications and in customers' expectations. This leads to more uncertainty in requirements.

To ensure all solutions are studied whatever future requirements may be, the design space needs to be enlarged. Instead of single values for the weighting factors that define the priorities, ranges around a given baseline inputted for both function and objective weighting factors are used.

A Design of Experiments (DoE) is then performed on those weighting factor ranges. A DoE is a systematic and efficient process for planning experiments so that the data obtained can be used to collect the maximum information about the design space with a minimum number of points. While numerous techniques exist to generate points in the design space, the latin hypercube is selected. This space filling DoE enables a rich and highly accurate sampling of the interior of the design space so that all solutions are studied. For each run of the DoE, the weights of all the functions and of the objectives are varied using the values from the latin hypercube.

As only non-dominated points are kept in the TOPSIS, the amount of cases studied is highly reduced, enabling a shorter computational time. Indeed, the TOPSIS is run for each possible combination so computational time becomes crucial as the number of alternatives increases. To select the most robust alternative, the overall ranking of each non-dominated alternative is computed by averaging its ranking for each run. The alternative which is the best on average (with the lowest average rank) is considered as the best robust alternative.

For the IFE system, a run with 10 different weighting factors for the functions and 10 for the objectives led to 100 calls of the TOPSIS and provided 23,320 solutions. If the full TOPSIS on all points would have been run, 665,400 calls would have been required, the number of points is thus divided by 28. After removing all the duplicates, when keeping only the non-dominated points, there are 320 concepts to study while when running the full design space, 6,654 concepts were to be studied, dividing the number of alternatives by 20. Therefore, keeping only the non-dominated points allows a considerable reduction of the execution time.

The comparison between the results of the Step 5 and 6 (Table 1) demonstrates the importance of the robustness analysis. Indeed, with a 30% variability around the baseline for both functions and objectives, important changes occur in the ranking. In particular, Concept 4384 is no longer the best one and is replaced by Concept 5383, which is more robust. In addition, Concept 4330 is no longer part of the top 5.

Table 1: Comparison of the top 5 concepts

Ranking	1	2	3	4	5
<b>Without uncertainty</b>	Concept 4384	Concept 5383	Concept 4375	Concept 5374	Concept 4330
<b>With uncertainty</b>	Concept 5383	Concept 4384	Concept 5374	Concept 4375	Concept 5362

## 4. Developed capabilities

As discussed in Section 2, current design environments fail to successfully support the development of innovative products. To address the identified shortcomings, a new methodology with key capabilities was developed and applied to the IFE system. This section aims at quantifying the contributions provided in various fields. These contributions are grouped into two main categories: decision-making capabilities and recommendations for the IFE design.

### 4.1 Dynamic and collaborative decision-making platform

The proposed methodology has been implemented into the integrated environment ASCEND that improves the communication between designers, marketing teams, and decision-makers. Indeed, ASCEND encompasses all design phases from the identification of customers' requirements to the selection of the best and robust physical architecture. The process follows a rigorous, documented, and quantitative approach so that decision traceability is highly enhanced. In particular, the following capabilities are provided:

**Exhaustive system definition:** Design objectives and requirements are propagated via a dynamic functional decomposition that can be saved in a common repository. Its implementation in ASCEND also enables a better visualization

of the functional decomposition and facilitates collaborative decisions during workshops. Finally, this systematic approach ensures the exhaustiveness of the decomposition and reduces the risk related to failures in requirements definition.

**Broader and more efficient design space exploration:** The use of the morphological matrix to generate alternatives provides a rigorous and systematic way to explore the entire design space. It also tends to attenuate designer bias since all possible combinations are considered. In addition, the compatibility matrix removes all unfeasible concepts so that the evaluation process is less time-consuming. As detailed in Section 3.3, the execution time of the overall evaluation process can be reduced by a factor of  $10^3$ .

**Integration of customers' needs within the decision process:** ASCEND is capable of automatically generating a survey that helps account for customers' preferences. Customers grade each option on a qualitative scale translated into a quantitative scale by ASCEND. This prevents project failures related to bad interpretation of the customers' voice.

**Consistent concept evaluation:** The proposed method is capable of consistently and quantitatively evaluating the various concepts against multiple objectives that cannot be easily compared such as customers' preferences, weight, and safety. In addition, this evaluation can use information from multiple sources: high-fidelity modeling software, designers' experience, and qualitative considerations.

**Rapid trade-off analyses:** Based on the previous concept evaluation, a visual representation of the different concepts in a two-dimensional space allows decision makers to easily perform rapid trade-off analyses. In particular, this environment supports collaborative decisions by quantifying interactions between objectives. For example, designers can evaluate the impact of improving performance on cost.

**Systematic concept selection:** The new framework provides the capabilities of systematically and efficiently ranking and selecting the best concept(s) based on a specific set of design priorities. The latter can be easily changed in order to develop multiple scenarios and assess their impacts on the physical characteristics of the best architecture(s).

**Integration of requirement uncertainty:** Since there is always uncertainty in requirements, the methodology allows designers to estimate the robustness of their selected concept(s). As such, even if requirements evolve or change, the concept(s) will still be the most suitable.

Fig. 7 summarizes the evolution in the number of concepts that must be investigated by designers. Among the 3 million possible combinations, only 320 can potentially be selected as the best concept. This shows how the execution time is reduced, while maintaining exhaustiveness in the design space exploration.

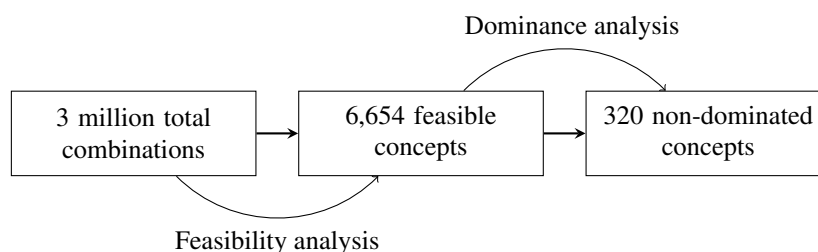


Figure 7: Summary of the concept selection process

## 4.2 Application to the in-flight entertainment system

The application of this new integrated, consumer-centric design methodology to the in-flight entertainment domain leads to the formulation of multiple recommendations for designers, manufacturers, and airlines. The selected solutions for each top-level function are as follows:

- To provide business-oriented service: ground communication and online catalogs to advertise products should be implemented.

- To facilitate the meal service: passengers should be able to order their food on their touchscreen and be alerted when the meal arrives so that they can clear their tray table.
- To provide multimedia contents: personal devices should be linked to the airline multimedia system for movies, games and e-books. In addition, the information about the flight can be given via the airline application that can be installed on the tablets.
- To provide passenger comfort: airlines could install external sensors plugged in the tablets that would monitor passenger's health conditions. Moreover, to reduce passengers' stress, airlines should increase the access to digital media.
- To support airline productivity: the link between flight attendants and passengers should be facilitated via the use of touchscreens where passengers can directly ask their questions or order food and drinks without having the flight attendant coming twice, to receive and deliver the order.
- To support airline profitability: airlines should provide a full internet access to passengers and maximize their attractiveness by increasing seat spacing.

## 5. Conclusion

Current design approaches usually result in failures caused by a lack of systematic methodologies that guide designers from the requirements identification to the concept selection. Indeed, none of the methodologies presented in Section 2 provide the capabilities of both keeping customers in the design loop and consistently comparing concepts against multiple objectives. As such, inspired by the quality function deployment, a new six-step methodology that follows the top-down design decision support process was developed. To support collaborative decisions, it has been implemented into an integrated environment: Architecture Selection based on Consumer Expectations and Needs to support Decision-making (ASCEND).

The proposed methodology starts with a dynamic functional decomposition that helps designers identify the required functions to exhaustively define the system. This decomposition is used to generate feasible concepts based on options for each identified function. It results in a broader and more efficient design space exploration. Each of these options are then graded and importance factors are assigned to functions and design objectives, allowing a consistent concept evaluation. To integrate customers' needs within the design process, a customized survey is automatically generated. Next, a multi-objective decision-making interface allows designers both to perform rapid trade-off analyses and to systematically find the best concept(s). Finally, the robustness of the selected solution(s) can be verified by taking into account requirements' uncertainty.

In-flight entertainment was used as a proof of concept and various recommendations are exposed. Undeniably, Wi-Fi and ground communications should be installed on aircraft. To make better use of new technologies, screens should be upgraded with tablets, and the meal service should be improved to facilitate flight attendants' job and enhance airline attractiveness. To conclude, the developed environment also intends to support the design of all products, especially the ones involving innovative technologies.

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