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Enhanced Basic Seat Assembly Concept Assessment: design methodology to advance civil aircraft seat installation

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Abstract

The Enhanced Basic Seat Assembly Concept Assessment is a design methodology applying Conceptual Design for Assembly theory to assess seats installation complexity in civil aircraft cabins. Initially assessing the installation process with only conceptual data, the method incorporates information across various levels of granularity, encompassing both conceptual and embodiment parameters. This research aims to include additional features to the original BSACA model as well as its software tool. The effectiveness of this approach was validated through different use cases (seats configurations based on airlines requirements), demonstrating the ability of the methodology in assisting seat concept assessment and redesign, yielding significant savings in time and costs throughout the Product Development Process.

Keywords: cabin equipment; design for assembly, design for manufacturing, installation, system engineering.

1. Introduction

In today's competitive manufacturing environment, conceptual design approaches have become cornerstones of efficient and cost-effective product development, as proved by several successful applications [1,2,3]. In the frame of aeronautics, a methodology, named Conceptual Design for Assembly (CDFA) [4], was tailored to respond to the urge of aircraft manufacturers to enhance their industrial performance while keeping costs, safety requirements, and manufacturing lead times under control. This is achieved through following four main steps, ranging from the product functional decomposition to the product architecture redesign. In that way, the CDFA overcomes the issues affecting standard Design For Assembly (DFA) methods [5,6] by shifting the focus on the earliest product design phases. Consequently, substantial expenses that might incur when developing complex engineering systems can be averted by controlling the assembly phase [7], which might impact up to the 40% of the final product cost [8]. However, this promising design methodology provides only general principles that have to be tailored to the specific entity of interest in order to be effective. Examples refer to aircraft nose fuselage [9] and cabin [10], with an individual research work carried out for seats [11]. Focusing on the last subsystem, the CDFA was used as a theoretical bases to root two interconnected methodologies. Firstly, the Systematic Knowledge Collection (SKC) approach [12] targets the issue of formalizing the data required to outline the criticalities affecting the Seat Installation (SI) process. Secondly, an operative design approach was defined by coupling the SKC with other CDFA principles, leading to the development of the Basic Seat Assembly Concept Assessment (BSACA) [11]. BSACA is a formal conceptual design methodology able to numerically quantify the criticalities affecting the SI process of a given seat

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concept, using the Likert scale to normalize miscellaneous parameters. As a result, a Final Score (FS) between 1 (i.e., the best concept possible) and 5 (i.e., seat characterized by a high SI complexity) is assigned to each concept to be evaluated, allowing engineers also to perform comparisons. Despite the good results achieved and demonstrated in [11], one main issue refers to the possibility to consider different levels of granularity in the input data with the objective to consider various design phases. To that end, the aim of this research work is to address the weaknesses of the BSACA related to: (i) increase the completeness of the knowledge data by including more detailed design attributes, whose different levels of granularity have to be properly managed; (ii) extend the mathematical model needed to compute the normalized values (i.e., Domain scores (Ds) and FSs) assessing the SI criticalities connected to each seat concept; (iii) develop a more user-friendly environment for data input and result analysis (i.e., software tool); and (iv) validate the new approach through the inclusion of additional case studies. The novelty of this design method lies in its use of parameters from not only the conceptual domain but also the early embodiment domain, which includes physical parts constituting seats. Due to the additional complexity, Python was identified as a suitable language program to code a new SI tool, made up of several Graphical User Interfaces (GUIs), guiding the user throughout the tool compiling process. The enhanced BSACA methodology and its software tool were validated by assessing four seat concepts, whose assembly criticalities were known since they had already been developed, deployed, and installed inside aircraft cabins. The validation phase done with aircraft manufacturer shows accurate results, especially in relation to the global scores used to rank and compare different variants. According to user feedback, the approach and its associated tool enable significant time savings during the conceptual design phase, streamlining the entire product development process. The presented paper is structured as follows: after this Introduction (§1), the proposed approach is presented in Material and Methods (§2) highlighting the improvements introduced. Then, the Results and Discussions (§3) are argued. Finally, Conclusion (§4) is presented containing the author's conclusion.

Nomenclature

i	generic domain number
j	generic major part attribute cluster number belonging to the i-th domain
m	total number of domains
n	number of major part attribute clusters belonging to th i-th domain
l	generic major part number
p	total number of major parts per seat
mps^l_{ij}	score of the j-th major part attribute cluster belonging to the i-th domain for the l-th major part
mps_{ij}	score for the j-th major part attribute cluster belonging to the i-th domain
k	generic seat attribute cluster number
q	number of seat attribute clusters
ss_{ik}	score for the k-th seat attribute cluster belonging to the i-th domain
D_i	generic i-th Domain score
r	generic seat concept
FS_r	Final Score for the r-th seat concept

2. Material and Methods

The enhanced BSACA methodology is constituted by four main phases: (i) Knowledge collection; (ii) Building of the data framework; (iii) SI tool development; and (iv) SI method and tool validation. Knowledge Document (KD) and the SI tool are the two outcomes of the presented approach.

2.1. Knowledge collection

The company's knowledge collected during the first SI study was extended through the interview of assembly experts in order to add more detailed design parameters. It emerged the possibility of improving the BSACA accuracy by involving attributes characterized by a lower granularity, in order to specify SI sub-steps involving several tasks. Due to the high number of design parameters and options to be analyzed, the SKC process already adopted [12] was expanded to include surveys to be administered to the blue-collars directly involved into the assembly operations. Thus, the *Attribute gathering* step of the extended SKC involves not only the inspection of assembly documents, plant visits, and brainstorming meetings with designers, but also the definition of a set of questions to be asked to the SI workers regarding the difficulty of carrying out each installation step. All the parameters characterizing the SI process were collected in a structured way and the assembly difficulties associated to those options were defined on the basis of the blue-collars' answers. Ten clusters of data (i.e., *domains*) were identified, as shown in Table 1.

Table 1. SI domains defined through the enhanced BSACA (A/C: aircraft).

ID	Name	Description
0	Initial Seat Information	Metadata
1	Seat Characteristics Definition	Main seat features influencing the SI process
2	Seat Splitting	Features hindering seat entry into the A/C
3	Seat Preparation to Enter the A/C	Features related to transport the seat into the aircraft cabin
4	Seat Entering & Positioning Inside the A/C	Feature related to enter the cabin door and position the seat
5	Installation & Positioning onto the Seat Track	Features related to securing the seat to its intended cabin component
6	Seat Connections	Features related to securing the seat to other cabin elements
7	Loose & Finishing Parts	Elements that dress the seat
8	Seat Protections for A/C Delivery	Seat protections for finishing parts
9	Test & Inspection	Functionalities of seat systems

2.2. Building of data framework

The major novelty of the Enhanced BSACA data framework is related to the introduction of *levels*, in compliance with the CDFA theory [4]. Two levels were required to deal with the different grades of detail characterizing the attributes. The main level, called *whole seat level*, comprises more general attributes related to the full seat concept. A second and lower *major part level* collects attributes detailing the parts composing each seat concept. Business Class (B/C) and First Class (F/C) seats can be made up of distinguished physical elements, called *major parts*, for manufacturability, assembly line constraints, and manoeuvrability reasons, although this is generally discouraged for simpler seats as Yankee Class (Y/C). Figure 1 shows an example of B/C seat consisting of two primary components: (i) the shell (grey-and-black part), designed to offer enhanced privacy, noise reduction, and improved comfort features, and (ii) the seat pan (red part), which is the main seating area for the passenger during the flight.

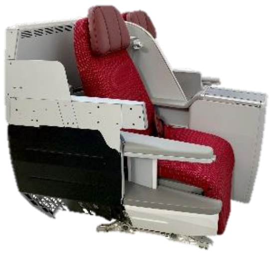

Fig. 1. Example of a seat made up of two major parts: (i) shell; and (ii) pan. © *Aviationscouts GmbH*.

In that case, attribute assessment requires to subdivide assembly parameters not only according to the specific sup-phase to which they refer (i.e., *cluster*) but also to their granularity *level*. For instance, attributes belonging to domain 2 (i.e., *Seat Splitting*) are listed in Table 2, specifying their name, belonging cluster, if they are defined for all the Seat Models (SMs) or only for specific ones, and their granularity level.

Table 2. Example of attribute subdivision according to their granularity level.

Name	Cluster	SMs	Level
Seat splitting needed Total number of major parts	Seat Splitting	All	1
Weight	N/A	All	2
Access Tool needed	Major Parts	B/C, FC	2
Adjustment system	N/A	B/C, FC	2
Fasteners & loose items for reassembly	N/A	B/C, FC	2
Electrical system reconnection	N/A	B/C, FC	2
Airbag to install	N/A	All	2
Location Quantity	Major Part System Interfaces	B/C, FC	2

In accordance with the definition of levels, the KD structure was modified to subdivide the two different attribute types, providing consistent explanations to motivate this clustering. The assessment of the assembly complexities linked to the design options associated to each attribute was carried out with the creation of several knowledge Scoring Matrices (kSMs), needed to normalize the miscellaneous parameters. The assembly criticalities introduced by each attribute variant are converted into a dimensionless number, comprised between 1 and 5 included. However, because of the introduction of levels, the resulting software tool to be developed to concretely perform the SI assessment requires a new management system. For this reason, a SQL database (*.db* extension) was created, thanks to its ability to store large volumes of data efficiently, while ensuring data integrity, such as in the case of attributes influencing other parameters belonging to different kSMs and domains. For instance, the *Seat Splitting* cluster was created as depicted in Figure 2, where the *ID* was used to allow the SI software tool to retrieve the *Score* associated to each combination of *Seat splitting needed* and *Split (Major) parts* options, varying according to the *Seat model* selected.

ID	Seat model	Seat splitting needed	Split (Major) parts	Score
1	Y/C	No	N/A	1
2	Y/C	Yes	N/A	5
3	B/C	No	1	1
4	B/C	Yes, but the seat split is not feasible ...	1	5
5	B/C	Yes, split is needed	2	3.5
6	B/C	Yes, split is needed	3 to 5	4.5
7	B/C	Yes, split is needed	6 to 8	5
8	B/C	Yes, split is needed	More than 8	5
9	F/C	No	1	1
10	F/C	Yes, but the seat split is not feasible ...	1	5
11	F/C	Yes, split is needed	2	3.5
12	F/C	Yes, split is needed	3 to 5	4.5
13	F/C	Yes, split is needed	6 to 8	5
14	F/C	Yes, split is needed	More than 8	5

Fig. 2. SQL database for the *Seat Splitting* cluster (domain 2).

The selection of *.db* databases was driven by their powerful querying capabilities, enabling complex data analysis through their seamless integration with other environments.

2.3. SI tool development

The presence of two attribute levels drives the novel mathematical model on which the enhanced SI tool is rooted. Domain scores (Ds) are computed, firstly, for the major parts composing the seat, secondly, for the whole seat concept. By doing so, the tool calculates a FS for each design, in compliance with the BSACA logic. Figure 3 depicts in detail the rationale used to compute the new Ds.

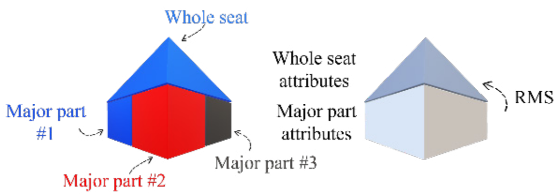

Fig. 3. Enhanced BSACA logic for domain scores.

Each seat is made up of p major parts, whose assembly criticalities are characterized through distinct clusters of attributes. Due to the their specificity and higher level of detail, the scores associated to the design options selected for the generic l-th major part (mps_{ij}^{l}) cannot be directly blended with the ones defining the whole seat (ss_{ij}), thus installation criticalities introduced by selecting different alternatives for the various major parts have to be preliminary averaged to obtain a single score. Following BSACA principles, the Root Mean Square (RMS) formula was selected:

$$mps_{ij} = \sqrt{\frac{1}{p}\sum_{l=1}^{p}\left(mps_{ij}^{l}\right)^{2}}, \qquad i \in [1, m] \text{ and } j \in [1, n]$$

where all the equation terms are defined in the Nomenclature section. At the end, a series of *major part scores (mps_{ij})* is computed, ranging from 1 to 5 as the other methodology scores. In that way, for each concept, every major part attribute cluster is associated with a single score, as for the parameters assessing the whole seat (ss_{ik}), making it feasible to aggregate them into a single and definitive domain score D_i:

$$D_i = \sqrt{\frac{1}{q+p}\left(\sum_{k=1}^{q}(ss_{ik})^{2} + \sum_{j=1}^{n}\left(mps_{ij}\right)^{2}\right)}, \qquad i \in [1, m]$$

The enhanced BSACA mathematical model was completed by the calculation of a FS for every r-th concept through the arithmetic mean formula:

$$FS_r = \frac{1}{m}\sum_{i=1}^{m} D_i$$

The computational framework required the building of several GUIs for data input. To accomplish engineering needs, results have to be presented to quickly identify areas for improvement. To achieve these results, the SI tool was developed by coding an appropriate program (i.e., Python), combining it with suitable software packages to display the intended outputs and to manage the knowledge data.

2.4. SI method and tool validation

The validation phase aimed at verifying the knowledge data and the mathematical model running behind the SI tool. Apart from the already-known sources of errors represented by the mean formulas selected, the kSM scores defined in conjunction with SI experts and workers, and the attributes mistakenly included or disregarded [11], the introduction of levels created the possibility of placing attributes in the wrong level. Considering that the enhanced BSACA development was motivated by the necessity of achieving more accurate seat FSs, in order to correctly rank all the seat concepts assessed, criteria (C) were set as part of the methodology itself in order to perform rigorous comparisons: (C1) different seat concepts can be compared only if they were developed for the same program type (i.e., long- or short-haul aircraft); (C2) different seat concepts sharing the same program type can be compared based on the airline company type that purchased them; (C3) different seat concepts sharing the same program type can be compared based on their seat model; (C4) different seat concepts sharing the same program type, airline company type, and seat model can be confronted based on any attributes belonging to domain 1-9 for which different design options were selected. Focusing on each criterion, C1 was stated by SI experts due to the marked differences between program types, in terms of requirements, airlines' and passengers' expectations, aircraft structure and so on. C2 was rooted on the hypotheses that four airline company types can be defined [11]: (i) high-end; (ii) middle-end; (iii) low-end; and (iv) low-cost. Despite this clustering was proved solid during previous BSACA applications, it should be refined through the adoption of commonly-accepted standards to neatly categorize every airline company. To this end, Skytrax, an independent UK-based consultancy specialized in the aviation industry, has proposed a global ranking system that evaluates airlines based on the quality of their services [13]. Even though this ranking is non-numerical, it constitutes a good starting point to order airline companies, since its symbolic rating (i.e., 5-star scale) is used to grade specific factors as cabin quality, seat quality, and In-Flight Entertainment systems. Through the integration of this information with publicly available data from each airline's official website, it is possible to methodically assess and rate the airline companies involved in the validation process. Moving to C3, simpler models should always have lower FSs and Ds if compared to more complex and deluxe seats. However, this holds true only when the airline companies being evaluated are of the same category. In cases where the airlines differ significantly in terms of their service offerings, the evaluation may yield varied results. Finally, condition C4 verifies when designers want to evaluate the possibility of either modifying an already-existing variant or improving a new seat that they are currently developing. These criteria should be always considered when evaluating the compliance of SI tool results, accordingly to the validation objectives, to be achieved through the careful selection of appropriate case studies, as done in section §3.

3. Results and Discussion

The validation phase was directed onto the two BSACA main outcomes: (i) the KD; and (ii) the SI tool. The related tasks were performed by applying the approach under examination to five use cases provided by a real aircraft manufacturer (i.e., AIRBUS). For confidentiality reasons, Greek letters are used to designate each seat concept: (α): B/C seat to be installed into a twin-aisle aircraft commissioned by a middle-end airline company; (β): B/C seat to be installed into a twin-aisle aircraft commissioned by a high-end airline company; (γ): B/C seat to be installed into a single-aisle aircraft commissioned by a middle-end airline company; (δ): B/C seat to be installed into a twin-aisle aircraft commissioned by a low-end airline company. These case studies were treated in two different ways. Firstly, a global assessment was performed to verify the correctness of the KD data (section §3.1), secondly, specific groups had to be defined to analyze the SI tool, in accordance with the criteria listed in paragraph §2.4. The α, β, and δ seat concepts were compared in relation to the different airline company types, while γ seat concept was redesigned according to new requirements established by the airline company that originally ordered the aircraft associated to γ.

3.1. Knowledge Document

Following the SKC approach, 21 attributes were determined as relevant to describe the SI process. Specifically, 19 attributes were used to detail SI criticalities (e.g., the possibility of having special links with aircraft monuments, requirements for additional systems to collocate the seat, or the need for supplementary assembly operations to complete fixing tasks). The remaining two attributes were metadata, thus not impacting onto the installation assessment. The design parameters were identified through the KD, specifying their level of granularity. Assembly domains were reorganized to be compliant both with the SI steps and assembly experts' suggestions, separating attributes in three main groups: (i) seat characteristics; (ii) mechanical and electrical connections; and (iii) complementary phases (e.g., handling, protecting, and testing). The impact of more important parameters, belonging to the second cluster, was enhanced and detailed by subdividing them into different domains, while less influential attributes, as the ones linked to protections, were incorporated inside other domains. By facilitating the identification concept weak points, engineers can more effectively address design issues, accelerating the entire seat development process. That approach can be extended to other cabin components, such as galleys, lavatories, and other integrated aircraft systems. While each entity retains unique design requirements and attributes, the core structure of the methodology remains applicable to a variety of complex systems. The organization of design parameters into domains ensures the achievement of a comprehensive framework, customized to fit the specific system needs. This, combined with the inclusion of attributes characterized by different levels of detail, allows engineers to optimize the design and assembly phases across various industries (e.g., aeronautical, naval, aerospace), thanks to the improvement of the whole PDP, leading to higher efficiency, reduced risks, and accelerated development timelines.

3.2. SI tool

The SI tool was implemented by integrating Microsoft Excel, used to generate an output file for the tool user, with two additional environments: (i) *SQLite* – lightweight, embedded, and self-contained relational database management system, to store kSM data, creating a *.db* file, and (ii) Python – programming language adopted to create GUIs, allowing users to input and normalize design options, compute associated Ds and FSs, and populate the file for displaying SI results. Focusing on the testing phase, the assessment of the four use cases resulted in a set of Ds and FSs (Fig. 4).

Use case	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	FS
α	1	2.2	3.7	1	1.8	2.4	2.1	2.3	3.1	2.2
β	2.9	2.9	2.3	1.8	2.9	2.4	2	5	3.8	2.9
γ	3	3	3	3	3	2.7	2.2	5	3.8	3
δ	2	1	1.7	1	2.3	1.4	2.6	1	2.8	1.8

Fig. 4. Domain and Final Scores derived for use cases.

This tool was tested by the same SI experts who provided the knowledge data gathered and formalized in the KD, with the objective of debugging the tool, improve its layout, and testing its mathematical model. As a demonstrative example, β's D_4 is detailed. To enter and position the seat and its major parts inside the aircraft, it might be necessary to remove cabin parts already installed for specific assembly constraints. In this case, no cabin parts were removed, leading to seat scores (ss_{41} and ss_{42}) equal to 1. Each major part has to be manipulated with a specific sequence of operations to fit the cabin door and alley. Only three out of the four β's major parts could be easily moved, resulting in the following scores: $mps_{41}^1 = mps_{41}^3 = mps_{41}^4 = 1$, $mps_{41}^2 = 4.5$, $mps_{42}^1 = mps_{42}^3 = mps_{42}^4 = 1$ and $mps_{42}^2 = 4.5$. In this way, all the mps_{4j}^l were averaged, with a result of $mps_{41} = mps_{42} = 2.4$, leading to $D_4 = 1.8$, as shown in Fig. 4. Globally, colors were used to identify a rank in terms of seat parameter redesign priority (Table 3).

Table 3. Color legenda for SI tool results.

Color	Range	Detected SI criticalities
Green	$D_i \leq 2$	No major or minor SI criticalities
Yellow	$2 < D_i < 4$	Minor SI criticalities
Red	$D_i \geq 4$	Major SI criticalities

Focusing on the FSs, according to the criteria formulated in §2.4, only α, β, and γ were eligible for comparisons.Given that their only difference is the airline type, an expected ranking of assembly criticalities can be defined based on this feature: (i) δ: simplest concept (i.e., lowest FS); (ii) α: intermediate SI complexity (i.e., intermediate FS); and (iii) β: most complex seat (i.e., highest FS). This could have been foreseen directly using the SI tool, by classifying the seat concepts in relation to their FSs. The compliance between the expected and the forecasted rankings proved that the addition of more detailed attributes had improved the model capabilities of computing accurate global scores. Nevertheless, the SI tool should also actively encourage engineers in the resolution of concept weak points. With this aim, γ was redesigned in conjunction with SI experts. Ds and FSs of the initial concept (i.e., γ) and its redefinition (i.e., ε) are depicted in Fig. 5.

Use case	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	FS
γ	3	3	3	3	3	2.7	2.2	5	3.8	3
ε	3	2.7	3	2.7	3	2.1	3.1	5	3.8	3

Fig. 5. Domain and Final Scores before (1st row) and after (2nd row).

Within the context of a possible redesign, the customer airline company requested a variant distinguished by more premium finishes and elevated features. For this reason, seat finishing parts were characterized by a higher installation complexity, leading to the necessity of performing the assembly tasks by using specific jigs to ensure that all the finishing parts are perfectly positioned and secured. These adjustment systems introduced additional difficulties, as testified by the D_8 score increment of 29%. To maintain limited SI cost and time, ε's FS had to be diminished or at least not increased, meaning that redesign actions had to be taken for the other domains. According to the airline company's requirements, it was not possible to modify the seat protections installed before delivering the aircraft to the customer (D_8), thus minor SI criticalities affecting domains 2, 4, and 6 were tackled. D_2 was improved by differently managing the seat splitting process, avoiding the necessity of performing electrical reconnection operations with a 10% reduction in result. The same was achieved for D_4, where the different seat splitting lead to major parts easier to be positioned inside the aircraft cabin. Finally, the seat was redesigned with the objective of avoiding additional seat equipment (e.g., screens, USB plugs), with a 22% improvement for D_7. This redesign activity demonstrated the potential of the SI tool in actively helping engineers in assessing and quickly improving the concepts developed during the earliest design stages, with possible high savings both in terms of time and cost. Despite these great outcomes, SI experts raised some minor concerns regarding the attribute allocation. Three attributes in D_2 should be redefined associating them to the whole seat rather than to the specific major parts, while other four attributes should be reviewed to specify the associated design options for each major part. Despite the minor effects on the mathematical model, due to the large number of unchanged attributes, these modifications are expected to enhance the capabilities of the SI tool in capturing even the smallest details of each concept. This, in turn, is likely to lead to a more precise identification of redesign opportunities, allowing for targeted actions.

4. Conclusions

The enhanced BSACA methodology was proposed to address assembly and installation challenges associated with aircraft cabin seats by optimizing their design process from the earliest stages. This approach operationalizes CDFA principles by introducing a method to quantitatively assess the SI criticalities related to specific design options selected by engineers. This is achieved through the definition of two levels that separate SI parameters according to their granularity, distinguishing between whole seat attributes and major part attributes. In this way, designers are able to evaluate different concepts by following the four enhanced BSACA steps. These steps are designed, firstly, to generate a repository containing the knowledge data to be retrieved during the quantitative analysis. Secondly, a database is constructed to allow the software tool to access the necessary information to normalize qualitative and quantitative design options. As a result, the SI tool can return dimensionless scores in its outputs, thereby guiding engineers in the assessment and redesign of their concepts. The final step aims at validating the full methodology and its associated software tool, addressing any formal issues. Through the analysis of four case studies, it was demonstrated that the enhanced BSACA methodology provides accurate scores and rankings for different seat concepts, assisting designers in identifying areas for review. The SI tool was proved effective as a redesign tool through the revision of one case study, following specific customer's requirements. Despite the positive results in terms of potential time and cost savings, some more improvements can be achieved. The knowledge collection process is still reliant on human evaluations, and consensus-building techniques should be incorporated to mitigate risks associated with human biases. Additionally, the SI tool should be revised in accordance with expert suggestions regarding GUI layouts, architectures, output displays, and attribute allocation. The reviewed SI tool should be tested with a wider range of case studies, particularly focusing on a variety of seat models. Furthermore, to fully demonstrate the potential improvements across the entire product development process, the SI scores should be quantitatively linked to the lead time required to complete SI tasks for each variant. Finally, the enhanced BSACA capabilities should be extended to other systems, such as trains, ships, and other complex means of transportation.

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