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Applying Trade-off Curve to Support Set-Based Design application in Aerospace Company

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Abstract

Companies compete greatly with each other today, so they need to focus on innovation to develop their products and make them competitive. Lean product development is the ideal way to develop product, foster innovation, maximize value, and reduce time. Set-Based Concurrent Engineering (SBCE) is an approved lean product improvement mechanism that builds on the creation of number of alternative designs at the subsystem level. These designs are simultaneously improved and tested. The weaker choices are removed gradually until the optimum solution is finally reached. SBCE implementations have been extensively performed in the automotive industry and there are a few cases studies in the aerospace industry. This research describes the use of trade-off curve as a lean tool to support SBCE process model in Configuration Optimization of Next Generation Aircraft project (CONGA), using NASA simulation software version 1.7c and CONGA demonstration program (DEMO program). This method will help designers and engineers to extract the design solution according to the customer requirement to achieve low noise engine at an aerospace company, and also extract the infeasible region where the designers cannot make any prototype in this region before manufacturing process begin, that will lead to reducing rework, time and cost.

Keywords: *Knowledge management, Lean product development, SBCE, Trade-off curve.*

1. Introduction

The lean knowledge management is known as an important condition that enables companies to obtain the right knowledge of the right people with form and quality at the right time. Significant enhancement of decision taking in product development is achieved when it is based on proven knowledge. This is achieved by creating a knowledge-based framework and knowledge visualization via the use of trade-off curves. Trade-off curves will allow designer engineering to compromise alternative solutions due to conflicting attributes in any aspect of the product lifetime [1]. Simply, the trade-off curve (ToC) is a tool to understand the relationship of various design characteristics to each other. They usually describe the link between at least two key factors that relate design decision(s) to parameter(s) that clients concern about over a set of values. Ward *et al.* [2] presented "set-based concurrent engineering", a procedure that demands various design solutions in comparison to conventional point-based product creation, to explain how

Japanese companies gain an advantage by relying on adequate information to postpone design decisions; the point-based approach restricts design space and offers less versatility in adapting design solutions among the different functions of product development. In comparison, a set-based approach allows product improvement functions to investigate design space and converge during the system narrowing process into an optimal design solution. To describe the knowledge environment, the researchers grouped methods and techniques in lean product creation into three main groups: decision-making, knowledge provision, and knowledge visualization.

Previous research work identified "trade-off curves" in various ways that are at some points identical to one another. For example, Sobek *et al.* [4] defined a "trade-off curve" as a relationship between two or more factors. According to Kennedy *et al.* [5], a "trade-off curve" is a relationship between two or more design decisions and is the knowledge of the subsystem from which design options are evaluated and narrowed until the optimal design is selected, thereby providing reusable information for future product design. Simply, it can be said that the trade-off curve is a tool to understand the relationship of various design characteristics to each other. Trade-off curves have a two-dimensional (2D) form and a multidimensional form.

Ward *et al.* [2], interviewed with Toyota's supplier, pointed the importance of trade-off curves. The teamwork of Toyota Company tried to reduce the noise with the Muffler. To reduce noise, they created back pressure in the exhaust and the gas flows out of the engine. Therefore, there was a trade-off between reducing the noise and creating the backpressure, and the backpressure reduces the performance of the engine. Haselbach and Parker [6], used a multidimensional trade-off curve to describe key technologies within aircraft engine combustion and core turbine systems contributing to low emissions products, fuel-efficient in the large civil aircraft engine market. Araci *et al.* [7], created a knowledge environment using trade-off curves during the early stages of the set-based concurrent engineering (SBCE) process of an aircraft jet engine for a reduced noise level at takeoff. Data was collected from a range of products in the same family as the jet engine. Knowledge-based trade-off curves are used as a methodology to create and visualize knowledge from the collected data. Findings showed that their method provides designers with enough confidence to identify a set of design solutions during the SBCE applications. Maksimovic [8], used a trade-off curve to capture the information when designing the structures of car seat. The capture of trade-off information involves the required sheet metal selection during the design of the structures of car seat, based on the criteria defined for the decision. Araci and Al-Ashaab [9], developed a systematic process for set-based concurrent engineering to develop a new product. They noticed that ToCs based on physics could help to define different product physics characteristics in the form of design parameters and visualize in a single graph for all stakeholders to understand without the need for a comprehensive background in engineering. Araci *et al.* [10], demonstrated the integrated use of ToCs in the SBCE process model in an industrial case study for a surface jet pump. The evaluation of a set of 60 different design solutions using a conventional approach could potentially be very resource-intensive; the application of knowledge-based and physics-based ToCs allowed the design-set to be progressively reduced until the optimal design solution was found.

As a result of the literature review, a research gap has been defined that "There is no clear framework and sequence of stages that will assist the creation and visualization of a knowledge environment to support set-based concurrent engineering applications". This research aims to construct a systematic approach for knowledge provision and visualization to support decision making in the early stages of "set-based concurrent" engineering applications via the use of "trade-off-curves (ToC)" during concept design of low noise engine identified decision criteria by designers and engineers. Trade-off curves will be based on these decision criteria (engine thrust force, bypass ratio, thrust specific fuel consumption (TSFC) and engine noise level), which is part of CONGA (Configuration Optimization of Next Generation Aircraft) project collaborated with aerospace company supported by Technology Strategy Board (TSB). The CONGA consortium has 6 industrial partners: Airbus, Airbus Group Innovations, Aircraft Research Association, Eurostep, MSC Software, and Rolls-Royce - including Cranfield University.

CONGA project aims to develop new multi-disciplinary design and integration processes to support the conceptual design and assessment of future aircraft configurations. Such developments are essential if designers are to be able to deliver robust product concepts (at the early stages of the design cycle) for novel aircraft and power plant configurations that embed new technologies.

2. The SBCE Process Model

The SBCE process model developed by Khan *et al.* [3] composed of principles which can be applied at the early phase of a development process [5], it consists of several key phases. Each phase is divided into activities, as shown in table (1).

Table 1,
The fundamental CONGA SBD process model.

1. Define Value	**2. Map Design Space**	**3. Develop Concept Set**	**4. Converge on System**	**5. Detailed Design**
1.1 Classify projects	2.1 Identify sub-system targets	3.1 Extract (pull) design concepts	4.1 Determine intersections of sets	5.1 Release final specification
1.2 Explore customer value	2.2 Decide on level of innovation to sub-systems	3.2 Create sets for sub-systems	4.2 Explore possible product system designs	5.2 Manufacturing provides tolerances
1.3 Align project with company strategy	2.3 Define feasible regions of design space	3.3 Explore sub-system sets: simulate, prototype, and test	4.3 Seek conceptual robustness	5.3 Full system definition
1.4 Translate value to designers (via product definition)		3.4 Capture knowledge and evaluate	4.4 Evaluate possible systems for lean production	
		3.5 Communicate sets to others	4.5 Design process planning for manufacturing	
			4.6 Converge on final system	

This study will explore the activities that trade-off curves can enable to support SBCE in the aerospace company as follows:

a. Choose the activity (2.3): Define a feasible region of design space.

b. Choose the activity (3.4): Capture knowledge and evaluate.

c. Choose the activity (3.5): Communicate sets to others.

d. Choose the activity (4.2): Explore possible product system designs.

There are many steps to construct ToC as shown in figure (1) to achieve low noise engine in CONGA project

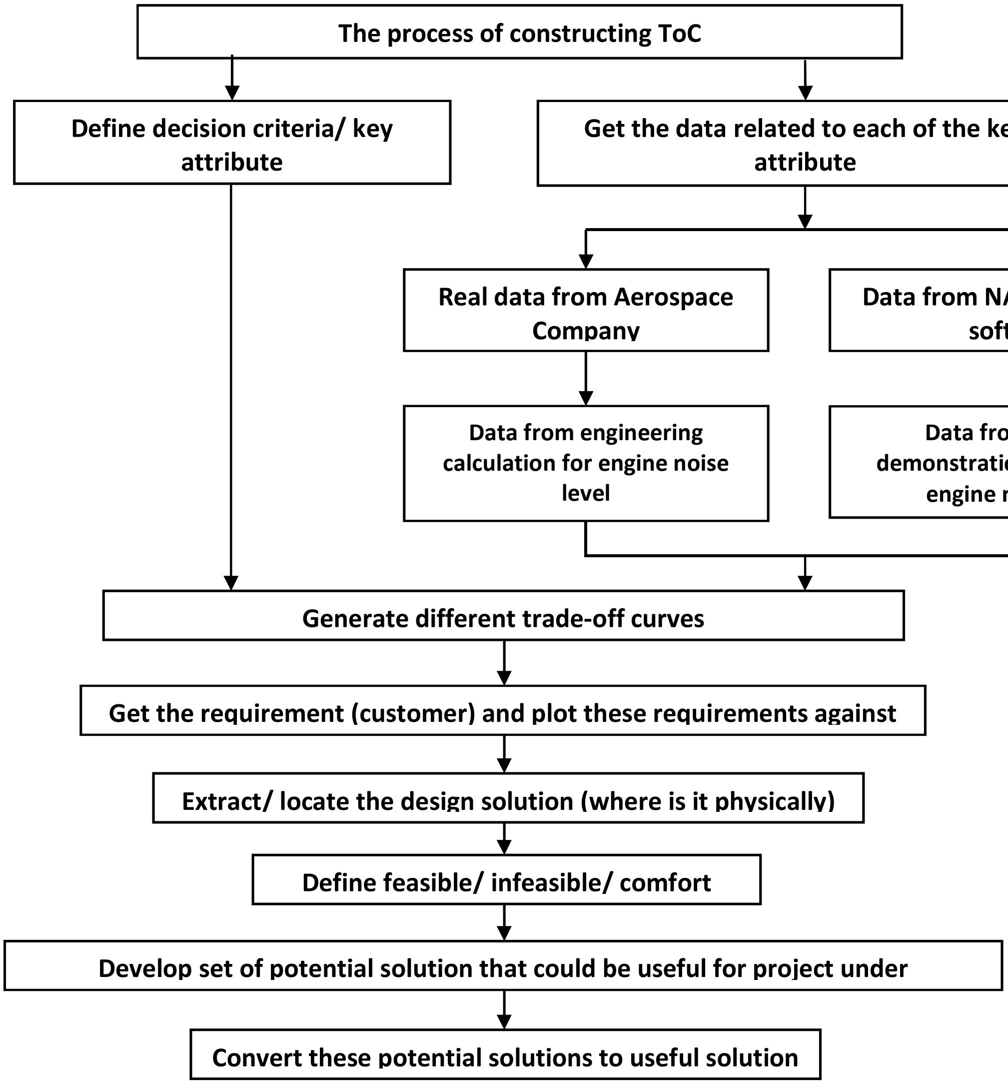

Fig. 1. The process of constricting ToC.

3. Defining Decision Criteria/ Key Attributes

Capturing of trade-off knowledge during concept design of low noise engine identified a decision criterion by designers and engineers. “Trade-off curves” will be based on certain parameters for decision (engine thrust force, bypass ratio, TSFC, and engine noise level).

Value of the four decision criteria were discussed with the designers and engineers at an aerospace company and they decided:

a. Engine thrust force is supposed to be high.
b. The bypass ratio must be high.
c. The engine noise level must be low.
d. TSFC is supposed to be low.

4. Getting the data related to each of the key attributes from the aerospace company

Data was compiled from the aerospace company for different types of real turbofan civil engines [11]; then data was extracted and eight different types of engines were selected depending on the highest maximum take-off mass (MTOM) for each type. Further data will then be collected from engineering calculation to compute the engine noise level for each type of real engine as shown in tables (2) and (3). The engine noise level was calculated as follows:

- **a.** Take-off noise (TO): 100% of the noise is engine noise.
- **b.** Approach noise (APPR): 50% of the noise is engine noise and 50% is airframe noise.
- **c.** Flyover noise (FO): 75% of the noise is engine noise and 25% is airframe noise.
- **d.** Cumulative noise: 100% TO + 50% APPR + 75% FO = Engine cumulative noise.

Table 2,
Data from an aerospace company certified by ICAO [11].

ID	Type	Version	Engine	Take-off Noise (EPNdB)	Flyover Noise (EPNdB)	Approach Noise (EPNdB)	Cumulative Noise (EPNdB)
AIRBUS_18615	A340	541	Trent 553-61	95.4	96.4	99.5	291.3
AIRBUS_18634	A340	642	Trent 556-61	95.8	95.9	100	291.7
AIRBUS_18642	A340	643	Trent 560-61	96.8	94.2	100	291
AIRBUS_18881	A330	341	Trent 768-60	96.9	89.6	96.9	283.4
AIRBUS_18817	A330	243	Trent 772-60	97.4	91.3	96.9	285.6
AIRBUS_20919	A380	841	Trent 970	94.2	95.9	98	288.1
AIRBUS_20928	A380	842	Trent 972	94.6	94.5	98	287.1
AIRBUS_20927	A380	842	Trent 972	94.5	95.1	98	287.6

Table 3,
Engine noise level of the real engine from engineering calculations [11].

ID	Type	Version	Engine	Take-off Noise (EPNdB)	Flyover Noise (EPNdB)	Approach Noise (EPNdB)	Cumulative Noise (EPNdB)
AIRBUS_18615	A340	541	Trent 553-61	95.4	72.3	49.75	217.45
AIRBUS_18634	A340	642	Trent 556-61	95.8	71.925	50	217.725
AIRBUS_18642	A340	643	Trent 560-61	96.8	70.65	50	217.45
AIRBUS_18881	A330	341	Trent 768-60	96.9	67.2	48.45	212.55
AIRBUS_18817	A330	243	Trent 772-60	97.4	68.475	48.45	214.325
AIRBUS_20919	A380	841	Trent 970	94.2	71.925	49	215.125
AIRBUS_20928	A380	842	Trent 972	94.6	70.875	49	214.475
AIRBUS_20927	A380	842	Trent 972	94.5	71.325	49	214.825

The CONGA Case-Study
Requirements or (customer requirement)
are as follows:

- a. Fan diameters between (2 – 2.5) m.
- b. TSFC: 0.055 kg/s.
- c. Low noise aircraft.
- d. Engine Cumulative noise limit for EU airports: 212 EPNdB.
- e. Engine thrust force variants (315– 320) kN.

ToC was drawn on three-axis by using MATLAB 8.4 software, the three-axis are decision criteria, the X-axis spouse to be engine thrust force, the Y-axis spouse to be either engine cumulative noise level or TSFC and the Z-axis spouse to be bypass ratio. By projecting the customer requirements against ToCs then the design required extracted physically in a faster and easier way and also other real engines that meet the customer requirement can be extracted to generate a set of possible solutions.

5. Results and Discussion

Trade- off Curve used to generate a set of solutions and also use during Set Narrowing as follows:

a. Mapping initial needs of customers versus the created trade-off curves give a collection of information that will create a set of design solutions. Such information is focused on the decision criteria that could relate to manufacturing process ability, test efficiency, material, and cost as captured in the trade-off curves shown in figure (2). The optimum solution for the decision criteria bypasses ratio and engine thrust force from trade-off curve one is Trent 772-60, which is meet the minimum customer requirements for bypass ratio and has high engine thrust force and good in engine cumulative noise level, but not good in TSFC, as shown in figure (3).

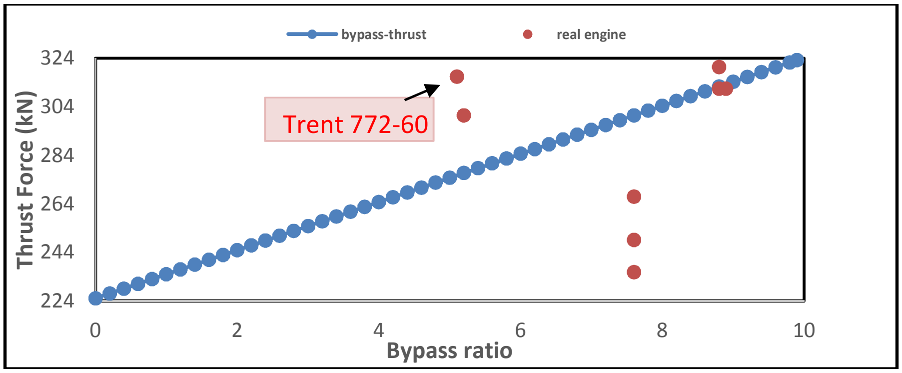

Fig. 2. Trade-off curve one between bypass ratio and engine thrust force with a real engine.

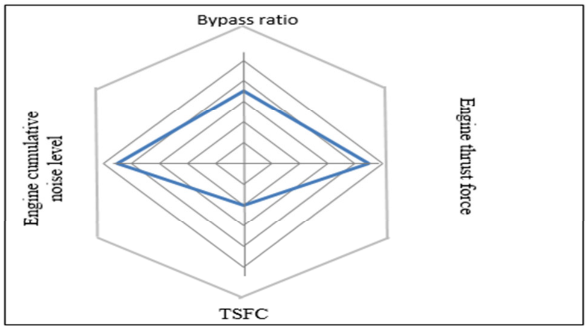

Fig. 3. Trent 772-60 optimum solution according to bypass ratio and engine thrust force.

b. The second Trade-off curve is between the decision criteria engine thrust force and engine cumulative noise level; the optimum solution from this curve is Trent 768-60 as shown in figure (4). Trent 768-60 has a higher bypass ratio and better TSFC than Trent 772-60, but not good in decision criteria of engine thrust force, and it is well for engine cumulative noise level, as shown in figure (5).

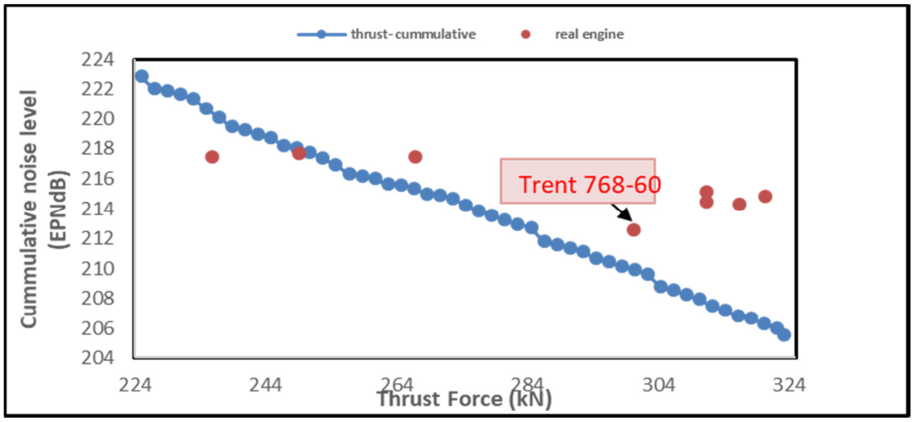

Fig. 4. Trade-0ff curve tow between engine thrust force and cumulative noise level with a real engine.

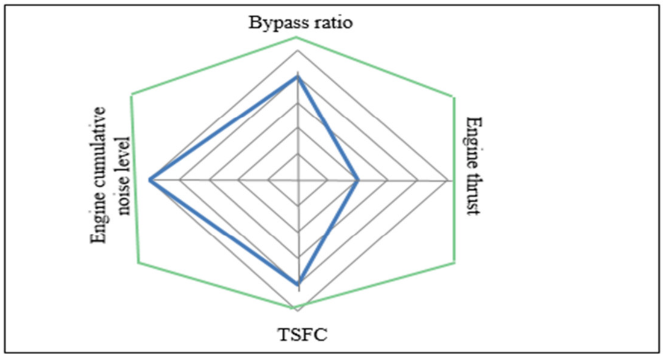

Fig. 5. Trent 768-60 optimum solution according to engine thrust force and engine cumulative noise level.

c. The third trade-off curve is between fan diameter and engine cumulative noise level; the optimum solution from this curve is Trent 560-61, as shown in figure (6). Trent 560-61 has a high bypass ratio, but not good for other decision criteria when compared to Trent 772-60 and Trent 768-60, as identified in figure (7).

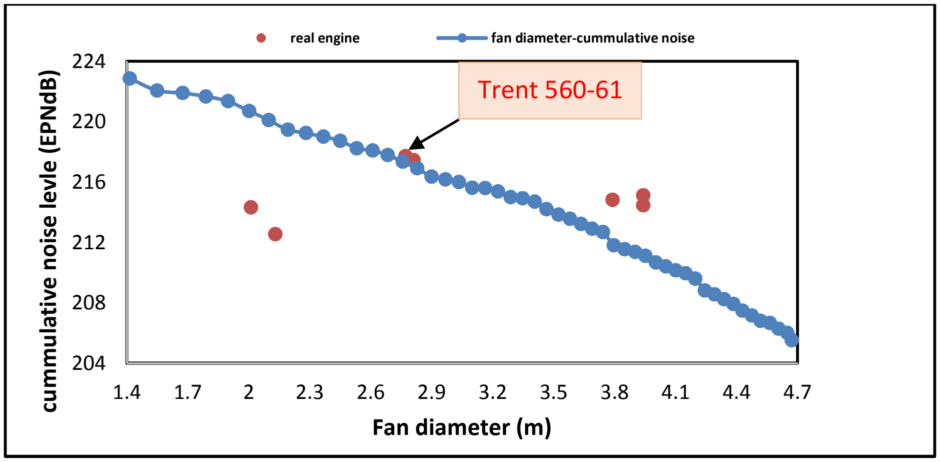

Fig. 6. Trade-off curve three between fan diameter and engine cumulative noise level with real engines.

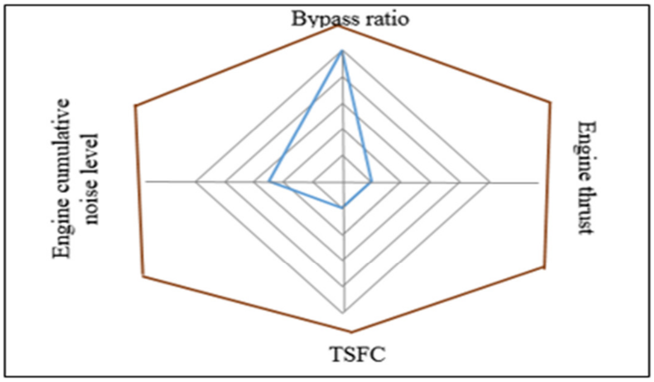

Fig. 7. Trent 560-61 optimum solution according to fan diameter.

d. The fourth trade-off curve is between decision criteria engine thrust force and TSFC; the optimum solution for these criteria is Trent972, as identified in figure (8). Trent 972 has high bypass ratio and meet the customer requirement for TSFC and engine cumulative noise level; Trent 972 is not well in engine thrust force as like as Trent 772-60, but better than Trent 768-

60 and Trent 560-61. Figure (9) illustrates Trent 972 according to the four decision criteria.

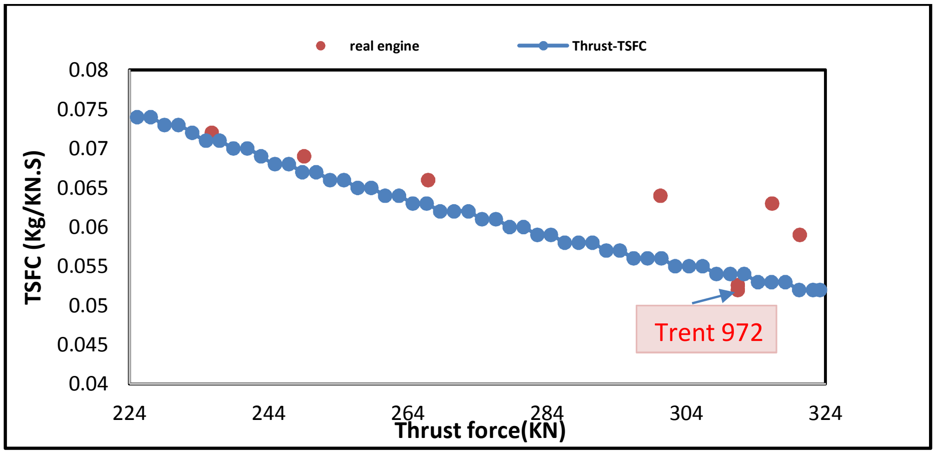

Fig. 8. Trade-off curve four between engine thrust force and TSFC with real engines.

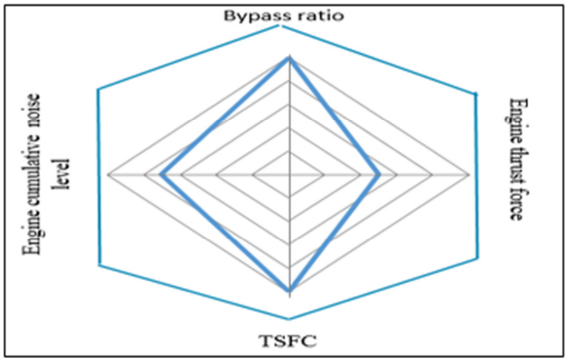

Fig. 9. Trent 972 optimum solution according to engine thrust force and TSFC.

The process for initiating a collection of resulting design solutions is the unavoidable conflict between different trade-off curves to provide the best suited design solution among certain trade-off variables as identity in figure (10).

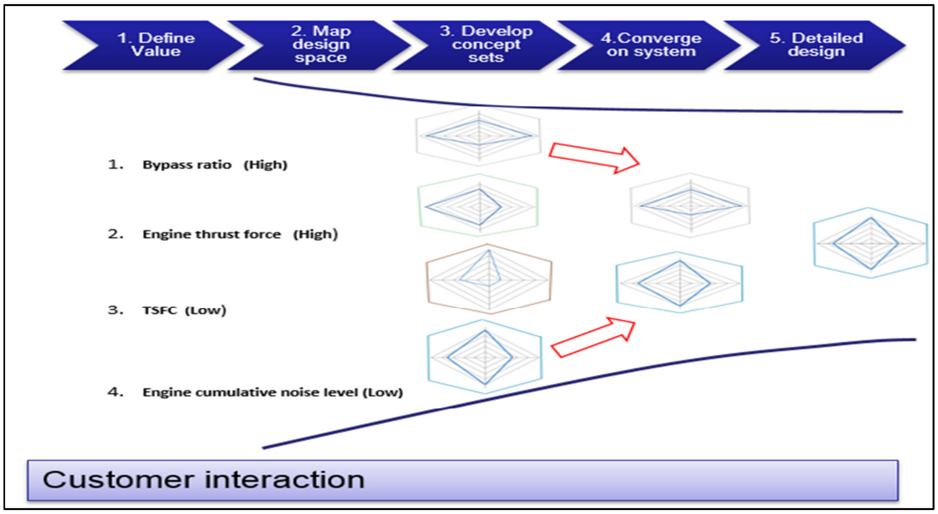

Fig. 10: Mechanism of narrowing set base design.

Throughout the face to face conversations, designers and engineers in aerospace company summarized four criteria for deciding according to the importance (bypass ratio, engine thrust force, TSFC, and engine cumulative noise level), depending on the importance of decision criteria, set of solution narrowed down from four solutions to two solutions (Trent 772-60 and Trent 972), by compromising engine thrust force. The optimum design solution was Trent 972 that meet the customer requirements.

6. Conclusions

To create better designs, it is critical to develop a methodology to discover, retain, organize, and present knowledge throughout all phases of the aircraft life-cycle. This methodology must consider knowledge management in the aircraft design, production, and operations to be flexible enough to capture the inherent variability of the system. The significant enhancement of decision taking in Lean product and process development (Leanppd) is achieved when it is based on lean thinking and implemented ToC as a source of knowledge to support value creation to the customers. The trade-off curves work so well because they combine the power of mathematics with the power of human visual processing system and can be visually displayed multidimensional in a single graph, that is mean we can generate ToC in 2D or 3D or multidimensional depending on the decision criteria, while visual cortex has a big part in the brain, mathematics has a small part, so by taking mathematics and putting it in the form of visual curves we can understand it faster.

The trade-off curve support SBCE process model by choosing some activities from this model, as generated set of solution to meet the customer requirement and then narrow down the set of solution to meet the customer requirement and then narrow down the set of the solution by depending on decision criteria until reach to the optimum solution.

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