Robust baseline design selection methodology: aircraft redesign case study

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Abstract. In product redesign process, the chosen baseline design plays an important role in determining the success of the development process. A good baseline design has a suitable level of architectural flexibility to absorb the change effect without propagating it beyond the initiating change components. Few methods for baseline design selection have been proposed but none of them consider the uncertainties of the change impact level during the assessment process. This study presents a robust baseline design selection method through a simple aircraft redesign case study that includes the consideration of change impact variation. The resultant distribution of the overall evolvability risk score for the baseline candidate can provide more insights on its suitability for the redesign task at hand. This allows a better selection of a more robust baseline design that lead a higher probability of product development success.

1. Introduction

Most available products in the market today are essentially the improved or upgraded versions of their previous predecessor designs. In other words, many of today's product manufacturers rarely start their design and development process from scratch. Instead, they utilize existing designs as the modification basis for improving them to be close to the new customer demands. For instance, aircraft or jet engines are exemplary complex products that have evolved from generation to generation through the transfer and revision of their design elements, ranging from general solution principles to details of component manufacture [1]. It has been conservatively approximated that more than 75% of design activities can be categorized as design modification, variant design or case-based design [2]. This highlights the high adaptation of redesign process in current product development, which is heavily driven by the market competition. Unlike a totally new product design and development, redesigning successful products by reusing their proven design elements and solution principles enables the process to be done faster and helps to leverage costs and risks [3]. Many redesigned products, although do not deviate far from their predecessor designs, are typically still perceived as novel by the customers.

One of the main differences between totally new and redesign product development is the existence of a well-defined baseline product design for the latter process. The complexity of the redesign process is closely tied to the appropriateness of the selected baseline design to the driving requirements. It has been demonstrated in a previous study that different baseline aircraft designs will have different level of redesign risks for similar development goals because of their different system architectures [4]. This particular condition is more pronounced in complex products since their design architecture is highly interrelated. The redesign process involves making modifications to the baseline design and due to the

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interrelationships between its parts or components, either physically or functionally, the effects of the changes made can be propagated to other parts or components within the system design architecture [5]. This phenomenon is known as "engineering change propagation" and it will adversely affect the budget and scheduling constraints of the redesign process. A good example on the negative impacts of the change propagation can be observed from the helicopter redesign case in the Westland Helicopters Company. From what should have been a simple redesign change to add the forward looking infrared radar (FLIR) turret, it has caused further modifications to its avionic, fuselage structure and nose cap, power supply, cabling and piping [6]. If the change propagation effects are underestimated, the impact to the product redesign development can be severe [7]. In general, the probability of occurrence of the change effects propagation is highly reliant on the level of connectivity between parts or components of the system design architecture and for redesign process, the interrelationships are very much well-defined for the existing baseline product design. For that reason, to reduce the effects of the change propagation, a better selection of the baseline design has to be made.

2. Previous works on baseline design selection methods

It is believed that baseline designs for redesign process are mostly selected based on their closeness to the target requirements or because they are the natural choice for incremental progression within their product family [8]. Such selection presumes that the imminence of the baseline's current capabilities to the driving requirements will ensure a minimum amount of required changes but, as the propagation of change effects goes, this assertion is not always true. A minor modification on existing product design can cause propagated changes to many other parts of the product while making a few major initiating changes may be limited to only the particular initial parts. This entails a careful look into the existing product architecture design in the selection of a good baseline design for redesign process and not just evaluating on the proximity of its current system performance to the target requirements.

The earliest work of the authors on baseline design selection comes as part of the development for the Strategic Planning of Engineering Changes (SPEC) methodology [9]. Realizing that the amount of changes to be made on the baseline product system also depends on its design architectural flexibility, several assessment metrics have been proposed to measure its goodness as the baseline for the specific redesign purposes. It should be noted that the suitability or goodness of the product system to become the baseline design varies for different redesign goals. The metrics: generality, scalability, adaptability, extensibility and complexity, have been primarily defined in reference to system evolvability measures in Ref. [10] and Methodology for Assessing the Adaptability of Products (MAAP) [11]. The definition of the baseline evaluation metrics is tabulated in Table 1. An example case of baseline assessment as a part of the SPEC methodology framework for aircraft system redesign process has been presented in Ref. [12], where it has been demonstrated with the use of baseline evaluation method that different baseline aircraft candidates have different level of redesign risks.

Table 1. Definition of baseline design assessment metrics [8]

Metric	Description
Generality	Capacity to accommodate changed or new requirements without requiring any changes to its existing design
Scalability	Capacity to accommodate required changes only by the scaling of its existing design without requiring any new components
Adaptability	Capacity to accommodate required changes without propagating the change effects beyond the initiating components
Extensibility	Capacity to accommodate required changes with the effects propagation allowed
Complexity	Capacity to accommodate required changes without increasing its design complexity level

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Using the same evaluation approach and principles, several assisting decision-making methods for product redesign process have been developed. These include Strategic Change Ranking Methodology (SCRaM) [13] and Change Ranking of Product Subsystems (CROPS) [14]. The work presented in this paper is essentially the continuation from a previous study in Ref. [15], where the Monte Carlo method is applied in the prediction of the subsystem redesign risk for complex products. The use of the Monte Carlo method here is to include the consideration of the uncertainty surrounding whether the redesign modifications made will introduce any propagated change effects to the adjacent parts or components. However, there are also uncertainties regarding the level of impact caused by the redesign changes that are not being considered. In previous studies, the change impact level is taken as a static value that has been predicted based on past design experiences, which might not be correct most of the times. Hence in this presented study, the change impact level is considered as a variable that has uncertain value and the resultant baseline product design from such assessment method is believed to be more robust with this additional consideration.

3. Robust baseline design selection

In general, the efficiency of the product redesign process can be estimated based on the amount of cost and efforts that it requires, which is translated into process risks when the redesigned product fails to meet all of the desired requirements. A widely-used scheme in risk management approximates change risk as the product of its likelihood and change rating [16, 17]. With this in mind, the prediction of the change impact from the product redesign works can be made through the translation of their level of difficulty and cost to realize them. Furthermore, the difficulty to implement the redesign changes can be related to the readiness of the technology to realize them. Based on this notion, the rating for level of change difficulty can be based on the definition of System Readiness Level (SRL). SRL is a good reference for qualitative change risk rating because it provides a great reflection of the change process at hand by relating to the system or technology readiness to be incorporated into the product's use [18]. Table 2 and Table 3 present the rating scale used for change difficulty and cost, respectively.

Table 2. Change difficulty rating scale

Rating	Description
1	The component modification is at SRL 5
4	The component modification is at SRL 4
6	The component modification is at SRL 3
8	The component modification is at SRL 2
10	The component modification is at SRL 1

Table 3. Change cost rating scale

Rating	Description
1	Very low cost
4	Low cost
6	Medium cost
8	High cost
10	Very high cost

Based on Ref. [8], the baseline design assessment metrics can be evaluated using the following Eqn. 1 to Eqn. 5. As can be observed from the equations, the inclusion of uncertainties with regards to change impacts will only affect the risk of adaptability and extensibility metrics whereas the risk of generality, scalability and complexity metrics remain as static values depending on the assessment of the redesign task at hand.

$$Generality\ Risk = \sum \begin{cases} 0 & no\ change \\ 100 & require\ change \end{cases} \quad (1)$$

$$Scalability\ Risk = \sum \begin{cases} 0 & no\ new\ component \\ 100 & require\ new\ component \end{cases} \quad (2)$$

$$Adaptability\ Risk = \sum [Cost \times Difficulty]_{no\ propagation} \quad (3)$$

$$Extensibility\ Risk = \sum [Cost \times Difficulty]_{with\ propagation} \quad (4)$$

$$Complexity\ Risk = \left(\frac{new\ no.\ of\ part}{existing\ no.\ of\ part}\right) + \left(\frac{new\ no.\ of\ interrelationship}{existing\ no.\ of\ interrelationship}\right) \quad (5)$$

The score of each metric is then normalized by dividing it with maximum possible penalty score as indicated by Eqn. 6. In the calculation of overall evolvability risk, each metric can be assigned with a different weightage as in Eqn. 7 to mark the importance level of each assessment metric according to the preference of the designer. The baseline product design candidate with the lowest evolvability risk score can be taken as the best.

$$Normalized\ Risk,\ x_i = \frac{Total\ Risk\ Score}{Maximum\ Possible\ Risk\ Score} \quad (6)$$

$$Overall\ Evolvability\ Risk,\ f = \sum w_i x_i \quad (7)$$

To better demonstrate the baseline product design evaluation process, along with the consideration of change impact uncertainties, it is shown through a redesign case study of an aircraft system.

3.1. Aircraft redesign case study

This redesign case study is presented to demonstrate the capability of the baseline assessment method in selecting the best baseline product design with regards to redesign tasks at hand. In this case, three candidate aircraft are being considered: Airbus A320, Lockheed L-1011 and Boeing 727. The redesign changes are driven by the need to implement the electrical-mechanical actuator (EMA) for the primary roll control mechanism. All of the existing baseline candidate aircraft systems are using hydraulically-operated actuators instead of EMA. The implementation of EMA will help to reduce the total aircraft weight. A MATLAB program has been developed to calculate the overall evolvability risk and it runs with the user inputs such as on the aircraft system architecture, and change cost and difficulty ratings for each of the considered subsystems.

For this case study, three aircraft design performance parameters are taken as design requirements: flight range, maximum passengers capacity and takeoff gross weight. Table 4 presents the assessment scores for generality and scalability metrics for all of the considered baseline aircraft candidates. For instance, the generality score for Airbus A320 aircraft is assigned as 100 with respect to flight range requirement because the current flight range of this aircraft is just 3000 nm compared to the required 3900 nm. It is impossible for this required performance improvement can be achieved by the existing design without requiring any system modification, hence the penalty score of 100 is assigned. On the other hand, for the same design requirement, the scalability score is assigned as 0 since it is possible to achieve improved flight range by scaling down the design. Note that each of the design requirements is assessed independently and should not be influencing the scores for other requirements.

For adaptability and extensibility assessment, all initiating change components of the candidates need to be first identified. In order to do this, the architectural design of the candidates has to be well-defined. In this case implementation of EMA within the candidate's primary roll control mechanism, other components that changed due to earlier changed components also need to be identified. In other words, propagation of the changes of the components has to be identified. These connections between the components can be mapped into the design structure matrix (DSM). An example for Airbus A320 aircraft as presented in Figure 1, where the symbol “X” in the DSM indicates the existence of a change relationship between components of both respective row and column. This indicates that changing the component of the column will subsequently induce a modification on the component in the row. For example, changing the left electro-hydraulic servo jacks will cause some modification on elevator and aileron computers component of Airbus A320.

Table 4. Assignment of generality (G) and scalability (S) scores

Requirement	Target	Airbus A320		Lockheed L-1011		Boeing B727-100	
		G	**S**	**G**	**S**	**G**	**S**
Flight range (nm)	> 3,900	100	0	0	0	100	0
Maximum passenger capacity	> 234	100	0	0	0	100	0
Takeoff gross weight (lb)	< 255,000	0	0	100	0	0	0
Normalized Score		2/3	0	1/3	0	2/3	0

		1	2	3	4	5
Captain Sidestick Controller	1					
First Officer Sidestick Controller	2					
Elevator and Aileron Computers	3	X	X			
Left Electro-Hydraulic Servojacks	4			X		
Right Electro-Hydraulic Servojacks	5			X		

Figure 1. DSM for primary roll control of Airbus A320

Based on system design architecture presented by the DSM, possible initiating change components in the implementation of EMA are identified and their change difficulty and cost ratings are assigned. Table 5 tabulates the rating assignment for the Airbus A320 system based on the rating scales in the previous Table 2 and Table 3. In a similar fashion, the change difficulty and cost ratings for the other two baseline aircraft candidates are also individually tabulated in Table 6 and Table 7.

Table 5. Change difficulty (D) and cost (C) ratings for initiating change components of A320

Initiating Change	Change Remark	Adaptability Assessment		Extensibility Assessment	
		D	**C**	**D**	**C**
Left Electro-Hydraulic Servojacks	Changed to EMA	4	6	4	4
Right Electro-Hydraulic Servojacks		4	6	4	4

Table 6. Change difficulty (D) and cost (C) ratings for initiating change components of B727

Initiating Change	Change Remark	Adaptability Assessment		Extensibility Assessment	
		D	**C**	**D**	**C**
Left Inboard Aileron Hydraulic Actuators	Changed to EMA	10	10	6	4
Left Outboard Aileron Hydraulic Actuators		10	10	6	4
Right Inboard Aileron Hydraulic Actuators		10	10	6	4
Right Outboard Aileron Hydraulic Actuators		10	10	6	4
Aileron Power Control Unit	Changed to electrical	10	10	4	1

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Table 7. Change difficulty (D) and cost (C) ratings for initiating change components of L-1011

Initiating Change	Change Remark	Adaptability Assessment		Extensibility Assessment	
		D	C	D	C
Master Aileron Hydraulic Actuators	Changed to EMA	10	10	6	4
Left Outboard Aileron Hydraulic Actuators		10	10	6	4
Right Inboard Aileron Hydraulic Actuators		10	10	6	4
Right Outboard Aileron Hydraulic Actuators		10	10	6	4
Master Outboard Aileron Servo	Changed to Electrical	10	10	4	1
Left Outboard Aileron Servo		10	10	4	1
Right Outboard Aileron Servo		10	10	4	1
Right Inboard Aileron Servo		10	10	4	1

To include uncertainty consideration into the change impact assessment, the assigned rating value is set as the mode value whereas 0 and 10 are taken as the lower and upper limits, respectively. With these known values, the best representative distribution for both change difficulty and cost ratings is a triangular distribution. Figure 2 depicts the triangular distribution for change difficulty and cost ratings with mode values of 4 and 6, respectively. Meanwhile, Figure 3 illustrates the resultant distribution of the product of the change difficulty and cost ratings. The adaptability and extensibility risk evaluation for all baseline aircraft candidates are calculated using the developed MATLAB computer program with the uncertainty consideration and the results are depicted in Figure 4.

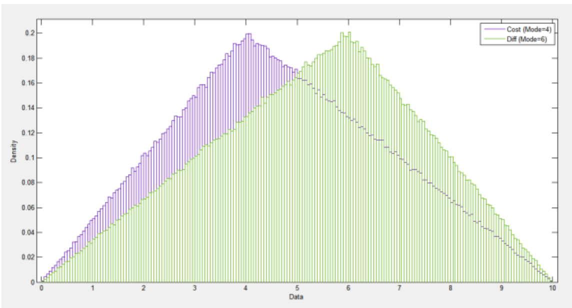


Figure 2. Example of a triangle distribution of cost rating with mode = 4 and difficulty rating with mode = 6

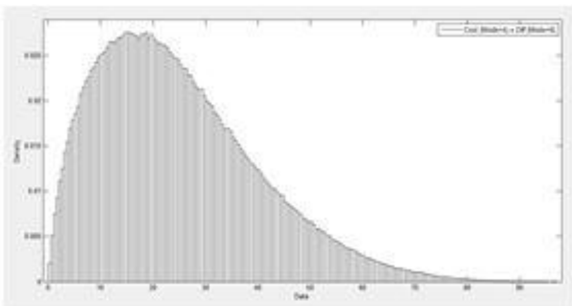
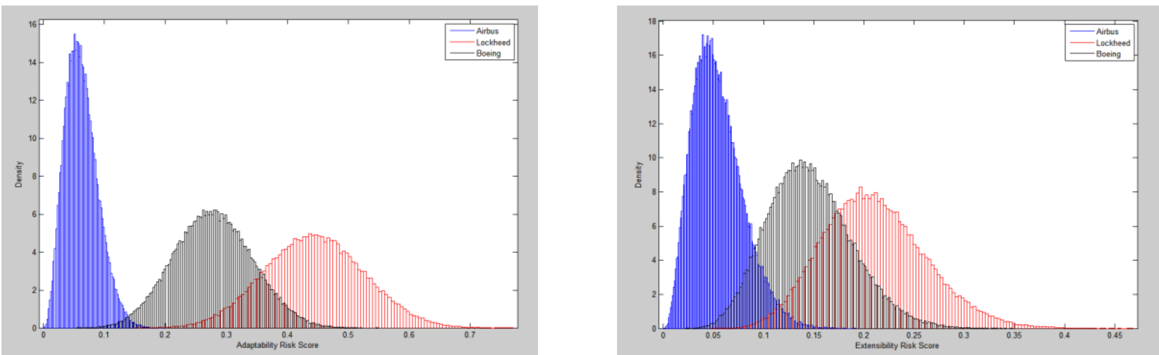


Figure 3. Example resultant distribution of product of cost and difficulty rating distributions in Figure 2



(a) (b)

Figure 4. Resultant output distribution for (a) adaptability and (b) extensibility risk scores

From Figure 4, it can be observed that there is an overlapping of risk scores between the considered baseline candidates, particularly for the extensibility metric, which is a sign that the aircraft might all have similar redesign risk level. Nonetheless, it is clear that Airbus A320 has the highest probability as the best baseline choice for this particular redesign task. Furthermore, Figure 5 presents the overall evolvability risk distribution for each aircraft that is computed using Eqn. 7 with an equal weightage for each of the five baseline assessment metrics (i.e. $w = 0.2$) at 1,000,000 random simulation runs. It can be observed that Airbus A320 is definitely the most potentially less risky for the redesign task as its overall evolvability risk score values are concentrated within the lower side of the risk distribution and hardly overlaps with the distribution of the other two. This makes it a robust choice as the baseline design for the redesign process.

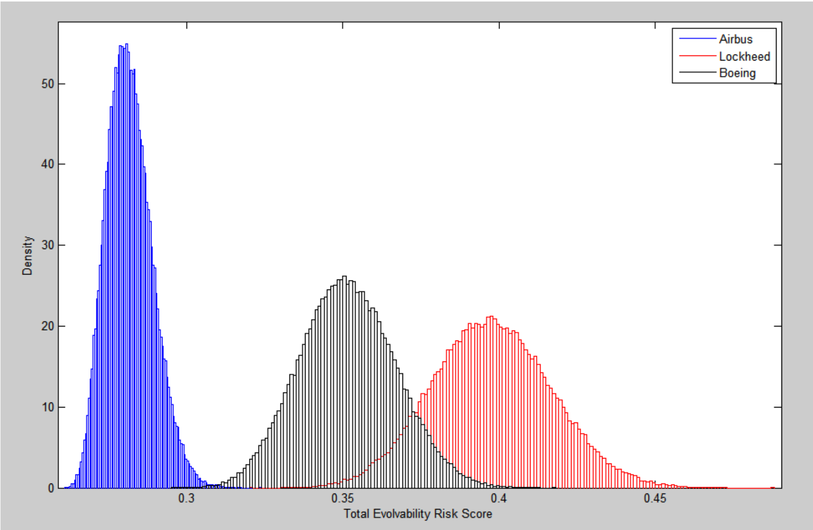


Figure 5. Total evolvability risk score distributions

3.2. Discussion
It can be seen from the results that Airbus A320 has the most potential for the baseline aircraft design to be used in the redesign case study, whereby its system design architecture is flexible and suitable in the EMA implementation process. The overall evolvability risk score distribution for the Airbus A320 is also not widely spread out and also highly concentrated with values in the lower risk region. These are good indicators that the aircraft redesign risk is of less uncertainties and highly probable to be of a low value. On contrary, distributions for evolvability risk score for both Lockheed L-1011 and Boeing B727 are rather spread out over the high values, indicating a high variability that might be harder to be comfortably predicted.

4. Conclusion
In this paper, the proposed robust baseline design selection methodology has been demonstrated using a simple aircraft redesign case study. Unlike static calculation for adaptability and extensibility metrics that have been done before, the impact of uncertainties of the change difficulty and cost ratings for the redesign task has been taken into account in this method. The resultant overall evolvability risk score distribution can provide more insights to the designer on the robustness of the baseline candidate to be used for the redesign development. This enables a better selection of the baseline design, hence leads to a more efficient product design and development process.

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