APPLICATION OF SUBSYSTEMS CHANGE RANKING METHODOLOGY IN AIRCRAFT REDESIGN PROCESS

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ABSTRACT: Redesigning an aircraft is hardly a straightforward task. Due to its high susceptibility to change effects propagation, it becomes very important to select the right initiating change components to minimize redesign development risks. With realization that there are often several different ways to redesign an existing aircraft for satisfying similar requirements, designers might require assistance in selecting suitable initiating change components in their redesign plan. A methodology that systematically ranks the subsystems of the chosen baseline design according to their estimated redesign risk is proposed here. It is strongly believed that making this information available to designers during the early redesign stages will help them to make a better redesign plan.

ABSTRAK: Reka semula sesebuah pesawat udara bukanlah satu tugas yang jelas dan mudah. Memandangkan ia mudah rentan terhadap perubahan rambatan, amatlah penting untuk memilih penukaran komponen yang sesuai pada peringkat awal untuk mengurangkan masalah pembangunan reka semula. Menyedari bahawa terdapat beberapa cara untuk mereka semula pesawat udara yang sedia ada, demi memperolehi keputusan keperluan yang serupa dan memberansangkan, pereka wajar mendapatkan bantuan dari segi penukaran komponen yang sesuai pada peringkat awal pembangunan reka semula yang menepati rangka pelan reka bentuk mereka. Metodologi yang sistematik meletakkan subsistem dasar reka bentuk yang dipilih, berdasarkan anggaran risiko reka bentuk semula dicadangkan di dalam kertas kerja ini. menolong pereka merangka pelan reka cipta yang lebih baik.

KEYWORDS: *subsystems ranking; aircraft redesign; redesign plan*

1. INTRODUCTION

Today, the main challenge for aircraft manufacturers is to develop their technologically sophisticated aircraft with affordable cost and in shorter timeframe [1]. High competition in commercial aircraft industry also introduces big pressure to reduce the development risk [2]. In conjunction to this, aircraft redesign is preferred than building new, original design from scratch. In addition to being cheaper and faster to be developed, derivative aircraft feature improved performance at lower risks and their commonalities to the predecessor designs help to avoid considerable increase in airlines' maintenance and operational costs [3]. Another attractive aspect of derivative aircraft is their design certification. Unlike an original aircraft design that is subject to many rigorous safety requirements, it is possible for the derivative aircraft design to benefit from past certification of its predecessor and avoid the stringent certification process. Observation on the current commercial aircraft market reflects the dominance of derivative configuration and this situation is expected to remain in the near future [4].

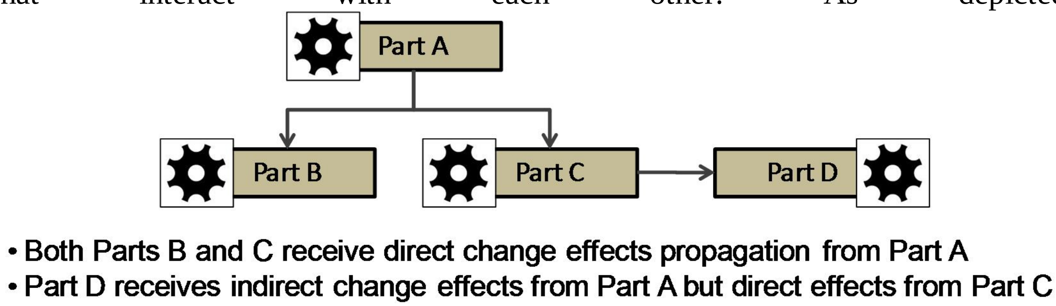
Since redesign practice is common in aircraft industry, its utmost benefits are typically gained by the fastest manufacturers to design and develop their range of market options without making costly mistakes. In this environment of design adaptation and variation, the handling of design changes becomes a key issue. The manufacturers' ability to address change requests from their customer airlines as early as during their negotiation process is essential to their market competitiveness [5]. A conducted study in Westland Helicopters Company highlights that 10% to 15% of their helicopter redesign costs occurred before the sales contract is signed [6]. It can be implied that the amount is spent on planning for the required change implementation and evaluating its possible side effects. Many engineering changes in aircraft development occur before the design gets to production floor [5]. Late design change, as suggested by the general "Rule of Ten" [7] in product development, will cost as much as 10 times higher than those made in the early stages. In redesign, existing baseline design is readily well-defined and lack of early design information is not an issue. Designers can use this information to fully capture the consequences from their redesign proposal and eliminate arising needs for late changes due to overlooked impact. With high constraints on time and resources, any mistakes in redesign planning could be detrimental to its success. To be able to compete with the relatively higher market interest for original designs, derivative aircraft design and development needs to be accomplished with lower costs and in a shorter timeframe. This means that the early redesign decisions have to be correctly made in order to avoid late changes and to minimize the overall redesign risks.

At the beginning of aircraft redesign process, designers have to decide on initial changes to be implemented into the baseline design that could improve its capability to satisfy the driving requirements. In general, this is hardly straightforward task because there are often a plethora of ways to modify the aircraft for the same requirements. For instance, if the total aircraft weight is to be reduced, designers have the options to minimize the weight of many onboard subsystems. The key question now becomes: which of these subsystems has minimum level of redesign risk when subjected to the intended changes? Each subsystem often has different levels of cost and design complexity; hence the change effects would also be different. Additionally, it can be observed that aircraft subsystems are highly and intricately interrelated. This makes its redesign process susceptible to change propagation phenomenon, which refers to the situation where an initial modification necessitates other major changes in the baseline design during its implementation. Hence improper choice of change initiating subsystem may produce additional side effects that can negatively affect the development efforts. Among others, these include an increased development cost and a prolonged development time. With its high design complexity and total number of parts that amounted to more than a million, the change decisions during aircraft redesign are not easy to make.

Driven by this realization, the Subsystems Change Ranking Methodology (SCRaM) is proposed as a decision-making aid for aircraft designers. In principle, SCRaM is a generic method that can be applied to any product redesign process. Nevertheless, in this paper, its application is highlighted for aircraft redesign process. Its application is expected to assist designers to identify the subsystems that could be changed with low potential risk for the redesign task at hand. Besides facilitating designers in selecting the initial changes, this method is also anticipated to improve the overall competitiveness of the aircraft redesign process by minimizing the development risk.

2. SELECTION OF INITIAL CHANGES IN AIRCRAFT REDESIGN

The challenges to redesign an aircraft system are mainly due to its multi-disciplinary nature, as characterized by the influence that its design disciplines have on each other. For instance, the aerodynamic lift and yaw moments drive the size of horizontal stabilizer and rudder, which in turn affects the design of flight controls system [2]. This condition also raises the possibility for change effects propagation, which is directly proportional to the connectivity level between parts comprising the design. The interrelationships between aircraft subsystems complicate its redesign with many potentially complex propagation paths that interact with each other. As depicted by



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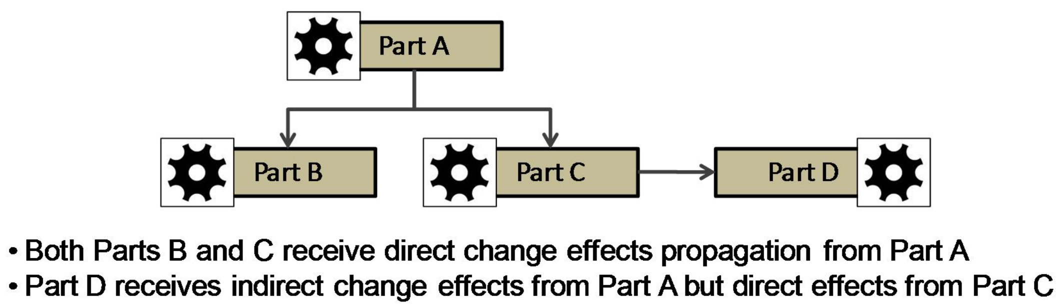
, change effects can be directly or indirectly propagated throughout the aircraft design architecture. Because of this, it is very easy for the redesign process to become mismanaged and consequently trigger unexpected changes due to any overlooked side effects from the initial change implementation. Some examples of drawbacks in the automotive and aeronautics industries due to mismanaged change process have been discussed in [8], which commonly sum up to cost increment and prolonged schedule.



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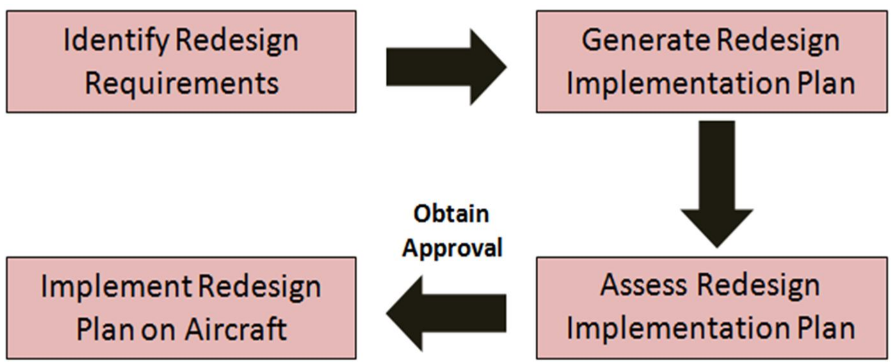
2.1 Change Initiating Subsystem

Ideally, the redesign planning process could be generalized as in **Error! Reference source not found.**. The first step is to identify and establish the customer or market requirements that are driving the needs to redesign the baseline aircraft. To satisfy these requirements, suitable redesign changes are planned. The proposed changes will then be assessed and the outcome from the evaluation process determines whether they are approved or disapproved for actual implementation. If approved, the proposal goes through a formal change management process before being applied into the derivative development. No iteration would be required if the proposal is good and the resultant derivative design is able to match all its driving requirements.

One of the first decisions to be made during planning of aircraft redesign is to identify the subsystems to be modified in order to satisfy the driving requirements. Since the cost and the process complexity to change the design of one subsystem is not similar to each other, different choice of initial change subsystem typically corresponds to dissimilar level of change effects and redesign risks. Moreover, the extent of potential change propagation between aircraft subsystems depends on this decision. Choosing a highly interconnected subsystem increases the possibility to affect many other subsystems. Overall, the selection of initial change subsystems has a big influence to the redesign development process. All efforts and resources spent could be wasted if an improper choice is made.



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To highlight the importance of selecting the right initiating component, consider the notional product architecture shown in

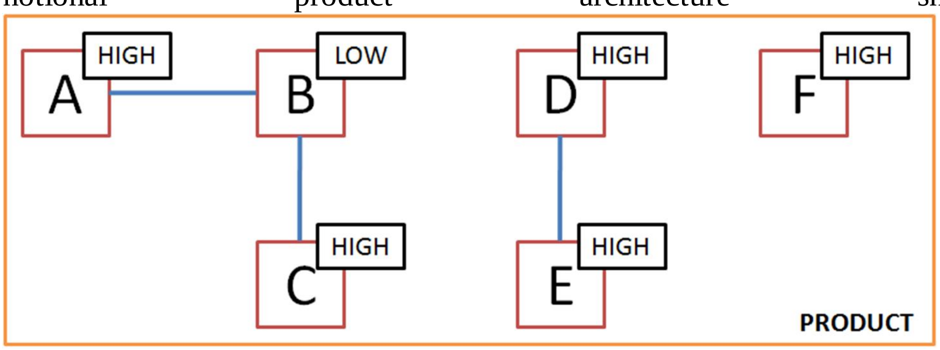


Fig. **1**. Each of its components has been arbitrarily assigned with a qualitative label that reflects on their difficulty to be changed. Assuming parts B, D and F can be equally chosen to undergo initial modification to satisfy the same driving requirement, it can be seen that each option will lead to different levels of redesign efforts. This is due to their degree of interconnections with each other. While part B has a low difficulty level to be changed, it can propagate the change effects to both parts A and C that are of high difficulty. On the other hand, parts D and F are both assigned with high change difficulty ratings. By changing part D, part E that is also of a high difficulty may be affected. Part F, despite having a high difficulty rating, is not connected to other parts and therefore contains the change effects to itself.

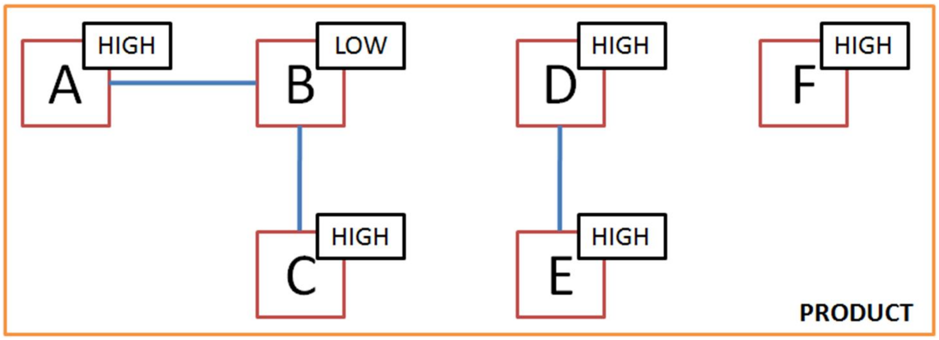


Fig. 1: Notional example product architecture.

It is evident in the above simple example case that the best choice of change initiating component is not straightforward, which is even harder to make in complex redesign tasks. The difficulty to modify the initial subsystem does not reflect on the full extent of redesign efforts that it will cause to the whole aircraft architecture. In short, this highlights the fact that selection of change initiating subsystem requires more considerations than just how difficult it is to change a particular subsystem.

2.1 Estimating Redesign Risk

In general, the required amount of redesign costs and efforts will translate into risks if the resultant redesigned product fails to meet all requirements even after the modification has been made. Based on a widely-used scheme within the product risk management field, redesign risk associated with changes on a particular component can be estimated by the product of its likelihood to be changed and the measure of subsequent impacts from those changes [9, 10]. In parallel to the interest of this study, derivation of change likelihood and impact parameters must reflect on the focus of initiating change decision. During decision-making process to choose initiating change subsystems in early redesign phase, the whole redesign plan is largely unknown. Hence the risk of selecting a particular initiating change subsystem has to be estimated without knowing for certain the other subsystems that are affected by its change effects propagation.

Knowing that propagation of change effects is only possible between two subsystems through their physical or functional links, the number of links can be taken as a descriptive measure for possibility of requiring changes. For instance, if subsystem A is not linked to subsystem B, then choosing subsystem A as the initiating change subsystem will not affect the latter. In the meantime, if A has interconnections to both subsystems C and D, the possibility of C and D to also require changes due to the propagated change effects from A is theoretically proportional to their interrelationship strength. This means, if subsystem A has more links to C than D, then change likelihood for C due to modification made in A should be higher than that for D. In addition, to capture the indirect change propagation effects in the estimation of redesign risk, change likelihood of subsystems throughout the possible propagation paths should also be taken into account. As the propagated effects are highly dependent on the change likelihood of previous subsystem in the propagation tree, the probability will cascade from the initiating change subsystem to those at the end of the propagation paths [11].

Based on the above arguments, change likelihood for subsystem *i* that is directly linked to initiating change subsystem *j* can be estimated using Eq. (1).

$$P_{ij} = \frac{Number\ of\ links\ from\ i\ to\ j}{Total\ number\ of\ links\ for\ i} \tag{1}$$

Meanwhile, the estimated change likelihood for subsystem *k* that is indirectly linked to the initiating change subsystem *j* through component *i* is given by Eq. (2).

$$P_{kj} = P_{ij} \times \left(\frac{Number\ of\ links\ from\ k\ to\ i}{Total\ number\ of\ links\ for\ k} \right) \tag{2}$$

For most engineering projects, the focus of risk analysis is often placed on the feasibility and the viability of the product design and its development process [12]. This can also be implied for aircraft redesign process. Following this argument, change impact measure can be based on the anticipated cost and the process difficulty to execute the modification. To support this, it has been proposed that the competitive measures for an engineering change process be reflected by the number of changes, the duration of its handling time and the required amount of cost or effort [13]. Naturally, a difficult design alteration also means higher costs and longer development time. However, recall that at this stage, information on the specific change type and level to be made is not yet available. Thus the assignment of change impact measure, designated here as *I*, can only be based on the assessment of available technologies and resources at the designer's disposal to execute the prescribed changes. A simple qualitative rating scale is employed here as in Table 1. According to this, the highly preferred rating is 1 while a rating of 9 is the least preferred.

Table 1: Change Impact Rating Scale.

Rating	**Description**
1	Change impact is expected to be very low and the subsystem is highly preferred to be changed in relative to others.
2	Change impact is expected to be low and the subsystem is preferred to be changed in relative to others.
3	Change impact is expected to be manageable and there is no preference in changing this subsystem relative to others.
5	Change impact is expected to be high and the subsystem is preferred NOT to be changed in relative to others.
9	Change impact is expected to be very high and the subsystem is

Rating	Description
	highly preferred NOT to be changed in relative to others.

Overall, the estimated total redesign risk, R associated with the selection of subsystem j as the initiating change subsystem, and its modification directly affects subsystem i and indirectly affects subsystem k through subsystem i, can be evaluated using Eq. (3).

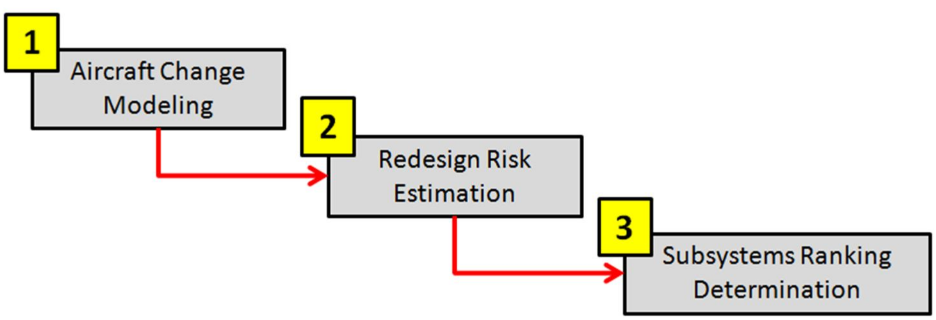
$$R_j = (1 \times I_j) + (P_{ij} \times I_i) + (P_{ij} \times P_{ki} \times I_k) \quad (3)$$

3. PROPOSED METHODOLOGY

The overall framework for the method is depicted in **Error! Reference source not found.**. In short, it starts with the aircraft change modeling process. Using the resultant model, the risk associated with the selection of each subsystem as the redesign change initiator is evaluated in a case-by-case basis. Finally, the results are used to rank the subsystems to identify the least risky one. The detailed description for each step of the method is presented in the following sections, which is supported with a notional sample case study.

Step 1: Aircraft Change Modeling

The objective of this step is to create a well-balanced aircraft model for predicting the change effects propagation and analyzing the associated change impacts to help support the decision-making process. Firstly, design structure matrix (DSM) representation has been chosen for the change model. At the moment, DSM is the best representation for use in the product engineering change study [14]. Secondly, the aircraft needs to be physically broken down in order for interrelationship links between its components to be identified. The model needs to at least capture the major components of its subsystems. Moreover, to be aligned with the real industrial practices, the aircraft system physical decomposition is tailored to the standard ATA 100 classification [15].



Error! Reference source not found.: Proposed methodology flowchart.

The summarized DSM representation of aircraft model to be applied in the subsequent sample case study is shown in **Error! Reference source not found.**, which involves only nine subsystems instead of the total aircraft subsystems. This is purposely done here to enable a better demonstration of the proposed method. In addition, note that modeling actual existing aircraft system is hard due to limited availability of descriptions in public domain regarding their full subsystems build-up. The next best thing is to create a notional aircraft system, which is modeled here using the generalized subsystem information of a few existing aircraft. In **Error! Reference source not found.**, each "X" mark indicates that the subsystems of respective row and column are interrelated such that change effects can be propagated between them. On contrary, empty boxes indicate no interrelationship between the corresponding subsystems. It is good to note that all indirect change relationships are not visible in this representation.

Error! Reference source not found.: DSM model of aircraft subsystems.

ATA	22	24	27	28	29	34	36	57	71
22		X	X		X	X			
24	X		X	X	X	X	X		X
27	X	X			X	X		X	
28		X							X
29	X	X	X				X	X	
34	X	X	X						
36		X			X				
57			X		X				
71		X		X					

ATA 22: Automatic Flight Subsystem, ATA 24: Electrical Power Subsystem, ATA 27: Flight Controls Subsystem, ATA 28: Fuel Subsystem, ATA 29: Hydraulics Subsystem, ATA 34: Navigation Subsystem, ATA 36: Pneumatic Subsystem, ATA 57: Wings, ATA 71: Propulsion

Step 2: Redesign Risk Estimation

Once the aircraft model has been successfully constructed, the next following step is to estimate each subsystem's change likelihood when one of them is subjected to changes. Referring to **Error! Reference source not found.**, each "X" mark is replaced by their corresponding change likelihood as estimated using Eq. (1). For the notional aircraft model used in this sample case, the calculated values are indicated in **Error! Reference source not found.**. Before redesign risk can be estimated, change impact rating for each subsystem has to be assigned based on the rating scale in Table **1**. Once this is done, overall redesign risk associated with the selection of each subsystem as the change initiator can be evaluated using Eq. (3).

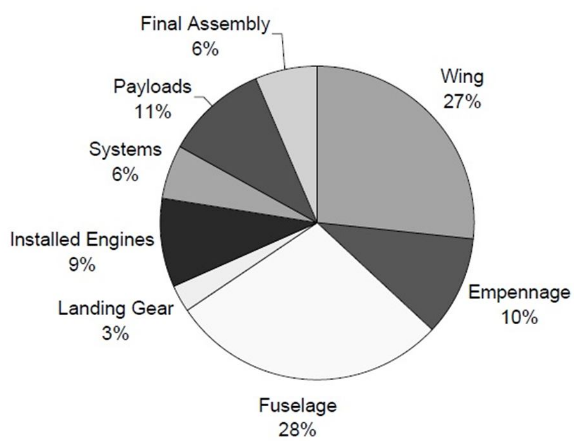
Error! Reference source not found.: Subsystem change likelihood.

ATA	22	24	27	28	29	34	36	57	71
22		0.04	0.12	0.00	0.01	0.82	0.00	0.00	0.00
24	0.04		0.04	0.04	0.03	0.04	0.03	0.00	0.02
27	0.12	0.04		0.00	0.28	0.02	0.00	0.07	0.00
28	0.00	0.04	0.00		0.00	0.00	0.00	0.00	0.05
29	0.01	0.03	0.03	0.00		0.00	0.01	0.09	0.00
34	0.08	0.04	0.02	0.00	0.00		0.00	0.00	0.00
36	0.00	0.03	0.00	0.00	0.01	0.00		0.00	0.00
57	0.00	0.00	0.07	0.00	0.09	0.00	0.00		0.00

71	0.00	0.03	0.00	0.05	0.00	0.00	0.00	0.00	

ATA 22: Automatic Flight Subsystem, ATA 24: Electrical Power Subsystem, ATA 27: Flight Controls Subsystem, ATA 28: Fuel Subsystem, ATA 29: Hydraulics Subsystem, ATA 34: Navigation Subsystem, ATA 36: Pneumatic Subsystem, ATA 57: Wings, ATA 71: Propulsion

In general, the assignment of change impact rating will depend on the redesign goals. Two scenarios are formulated for the example case study to observe the sensitivity of the proposed method in capturing different preferences and objectives of the redesign process. The first scenario assumes that all subsystems have equal level of expected change impact and there is no obvious change preference between them. This condition is captured by assigning the change impact rating for all subsystems as 1. On the other hand, the second redesign scenario is linked to the cost factor. Subsystems with high development cost are taken to be more expensive to be changed and thus they are preferred not to be affected in the aircraft redesign planning. The assignment for this second scenario is made based on cost breakdown in **Error! Reference source not found.**, which is the fractional manufacturing cost of the Boeing B777-200 aircraft. All in all, **Error! Reference source not found.** summarizes the assignment of change impact rating for the two scenarios.



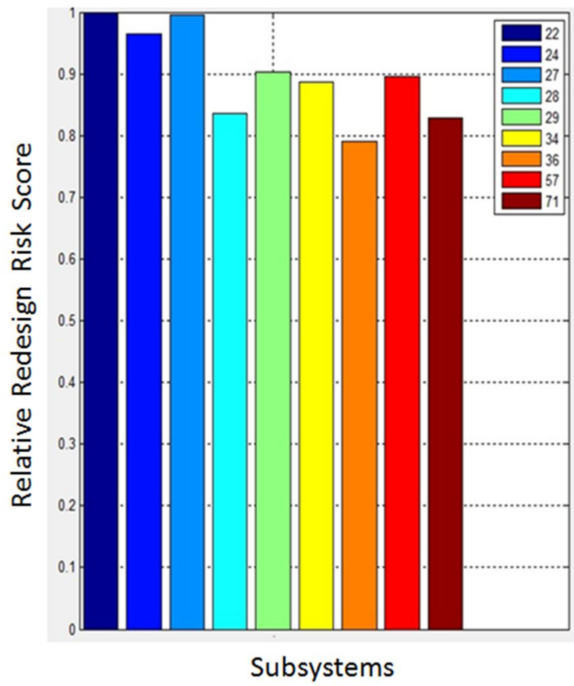
Error! Reference source not found.: Manufacturing Cost Breakdown of B777-200 Aircraft [16].

Error! Reference source not found.: Assignment of change impact rating.

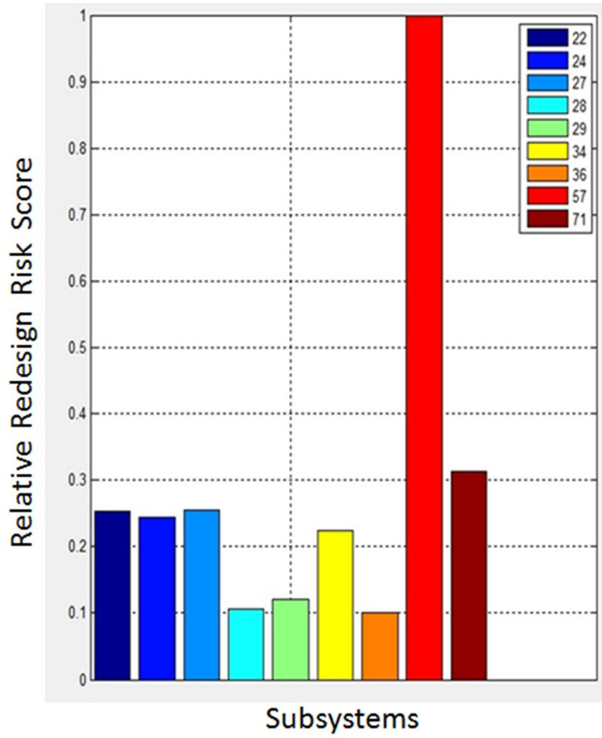
ATA	**Change Impact Rating**	
	Scenario 1	***Scenario 2***
22	1	2
24	1	2
27	1	2
28	1	1
29	1	1
34	1	2

ATA	Change Impact Rating	
	Scenario 1	***Scenario 2***
36	1	1
57	1	9
71	1	3

The redesign risk is then calculated using the likelihood and impact rating values. For this study, a MATLAB program is developed to calculate redesign risk based on the user-defined model and impact rating inputs. The results for the first scenario are presented in **Error! Reference source not found.**, which is plotted in relative measure against the highest calculated risk value. In similar fashion, results for the second scenario are shown in . Based on this, ranking of the subsystems in terms of their estimated redesign risk can be established.



Error! Reference source not found.: Relative redesign risk for scenario 1.



: Relative redesign risk for scenario 2.

Step 3: Subsystems Ranking

In **Error! Reference source not found.**, the automatic flight (22) and flight controls (27) subsystems have the highest redesign risk, as both correspond to the relative risk score of 1. On the other hand, the lowest ranked subsystem with respect of being risky to be redesigned is the pneumatic (36) subsystem. To interpret this result, recall back the settings for the first scenario in which all subsystems are assigned with the same impact rating of 1. For this particular condition, the estimated redesign risk heavily depends on the likelihood that the choice of one subsystem as the change initiator will subsequently affect other subsystems. In other words, the resultant ranking reflects on the risk of having to change other subsystems as a result of choosing a particular one as the initiating subsystem. Based on the constructed notional aircraft model, both auto flight and flight control subsystems comparatively have among the highest number of interrelationships with the other subsystems. In contrast, pneumatic has the least amount of interconnections. This is also reflected by **Error! Reference source not found.**, which means that the results are in line with the expectation for this particular scenario.

For scenario 1, based on the resultant ranking, choosing auto flight and flight control as the change initiating subsystem corresponds to the highest redesign risk among the nine considered subsystems. On the other hand, pneumatic has the lowest risk if chosen as the change initiator. Hence given a redesign task where either one of the nine subsystems can be chosen to be initially changed (such as to reduce aircraft empty weight), then pneumatic appears to be the best choice since any changes made to it will not affect most of the other subsystems.

On the other hand, scenario 2 mimics the sole consideration of risk due to anticipated development costs. Referring back to **Error! Reference source not found.**, it can be observed that the results are in good agreement with the cost breakdown. Wing (57) is decidedly the costliest subsystem to be modified and therefore scores the highest redesign risk as shown in . This is despite the fact that changing the wing will not affect as many subsystems as the other eight. On the other hand, observing the risk scores for automatic flight (22), electrical power (24), flight controls (27) and navigation (34); their differences can be contributed to the risk of their propagated change effects. Though they all are assigned with similar change impact rating (they are perceived to be of similar level of change cost), their interrelationships to other subsystems are affecting their risks valuation. Comparing the electrical power and flight controls, for instance, the former gets a lower risk score despite having more links to other subsystems than the latter. It could be argued that this condition happens because, though selecting electrical power also means requiring more subsystems to be redesigned than that imposed from the selection of flight controls, most of its directly and indirectly affected subsystems are of low impact ratings. Hence its overall redesign risk is lower than that of flight controls.

On the whole, given a redesign task where cost is the main factor for manufacturer and any one of these nine subsystems can be selected for modification, wing is not the best choice as it incurs the highest redesign cost. Alternatively, pneumatic or fuel is the best choice with the cheapest estimated costs.

4. CONCLUSION AND FUTURE WORKS

This paper proposes a simple yet powerful methodology to assist aircraft designers in deciding on the proper initiating change subsystems during the early redesign stages. The resultant ranking from this method allows designers to gain an insight on how risky it is to choose the subsystem for initial redesign task. Definition of risk here can vary depending on the designer’s redesign goal, as demonstrated by the sample case study. The formulated scenarios represent two different redesign process concerns, which correspond to different results. This adds to the flexibility of application for this proposed method. On the whole, the resultant ranking can be used by designer to support their decision-making process as to which subsystem is the best choice to be initially changed such that the incurred risk is low.

The results for the sample case study are in line with expectations. Nonetheless, having only nine aircraft subsystems instead of the total 34 makes the results too predictable and is not truly representative of the difficulty level of such redesign decision-making process. In addition, these subsystems also have interrelationships to the other subsystems that are not being considered in the sample case study, making the resultant ranking less reflective of the one for the whole aircraft because some propagated change effects (on subsystems that are not considered) are clearly ignored. While the sample case study is believed to be adequate to demonstrate the applicability of the proposed method, the natural next step is to apply it to the full extent of the aircraft subsystems build-up.

It is realized that the precision of results from this proposed method highly depends on the inputs for the change impact rating. While the example case study utilizes a simple qualitative rating scale to facilitate the assignment of this impact rating, more standard and structured scheme is needed to ensure the precision and the consistency of the results. This is among the areas to be further improved in the future for this proposed method.

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NOMENCLATURE

P_{ij}	change likelihood for subsystem *i* due to initiating change subsystem *j*
I	change impact rating
R_j	estimated total redesign risk associated with the selection of subsystem *j* as the initiating change subsystem