Functional Analysis for Conceptual Aircraft Design

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***Abstract*—To maximize the aircraft market potential, it has to be rapidly produced and made available in the market. In order to reduce time-to-market period, manufacturers need to shorten their design and development process. It becomes vital that the design architecture solution is derived faster, which can be quite handful for complex products like an aircraft with the current geometrical-based approaches due to the plethora of physical alternatives to be considered. On the other hand, the search for design architecture solution from the functional requirement is theoretically more effective since the functional space is smaller than physical search space. This allows the design efforts to be more focused and subsequently saves time, effort and resources. With this notion, there is a motivation to adapt the functional approaches into the conceptual product design process in order to exploit some of its advertised benefits. In this paper, a sample case study of an aircraft functional analysis and the discussion on how this information is useful during the conceptual design stage are presented.**

***Index Terms*—aircraft system, functional analysis, conceptual design, functional breakdown**

I. Introduction

Due to market changes in the last decades, manufacturers need to revise their product development practices to survive new competitive environment that is largely characterized by increased demands for higher design variety and complexity, shortened production time and intensified global competition [1]. For aircraft manufacturers, the twin business challenges today are to design and develop their aircraft with affordable cost and within much shorter timeframe [2]. In the complex product manufacturing like aircraft, improvement in design productivity will also govern the improvement of its industrial productivity [3]. Among others, this means that exploration of potential design solutions during the conceptual stage needs to be made more effective and faster, without sacrificing the design freedom to promote innovative ideas. Plus, the aircraft design concept selection and development process needs to be supported with reliable methods and tools that assist designers in avoiding costly mistakes while fully exploring the design space for the optimum solution.

In many respects, products today have been fundamentally redesigned or physically inspired from existing predecessors in the market. This puts a higher emphasis on physical aspects of product design in constraining the development process. The process needs to be worked around accommodating these physical constraints since the primary idea of redesigning is to not make any unnecessary design changes [4]. Although this helps to ensure that the resultant product design will work to a certain extent, it certainly limits the designers in finding new, innovative solutions.

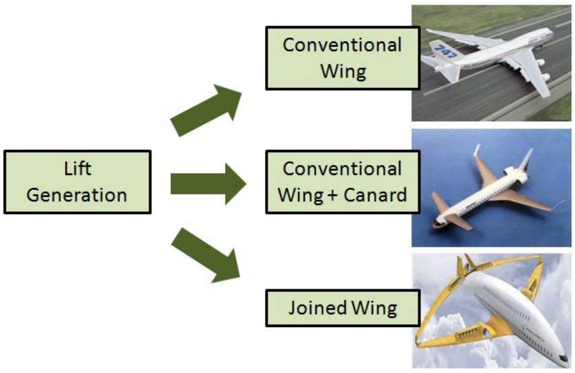

Figure 1. Example of different ways for lift generation.

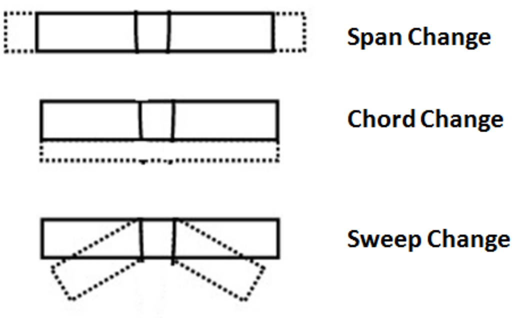

Figure 2. Change of several conventional wing parameters.

On the other hand, exploration of potential design solutions through the functional space is believed to be more flexible. Indeed, physical descriptions of product design are supposed to be driven by its functions; hence the latter should become the constraint of the design process

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rather than the former. Moreover, the functional space is arguably more generic and therefore allows more flexible conceptual building blocks when exploring all potential design solutions. As depicted in Fig. 1, functional requirement to generate lift for aircraft can be achieved in several ways. However, if the designer readily has conventional wing design as the final physical realization, it limits the search for innovative design solutions to only the variations of parameters for the conventional wing design as shown in Fig. 2. This paper intends to highlight the potential benefits that could be obtained by exploring the conceptual design space through functional analysis.

II. Functional Analysis of an Aircraft

Many aircraft subsystems are interconnected through their functions. These subsystems level functions will build up the capability of the aircraft system to accomplish its operational mission. In normal design process, the intended performance of the aircraft will determine the required subsystems level functions. For a weight-sensitive product like an aircraft, the required aircraft system level functions play an important role in selecting what subsystems should be incorporated into the design. If any subsystem is unnecessarily installed, it will just needlessly increase the aircraft weight without contributing to its mission. Therefore, functional analysis during conceptual design phase is vital to ensure that the physical aircraft design manifestation is done in an optimized manner.

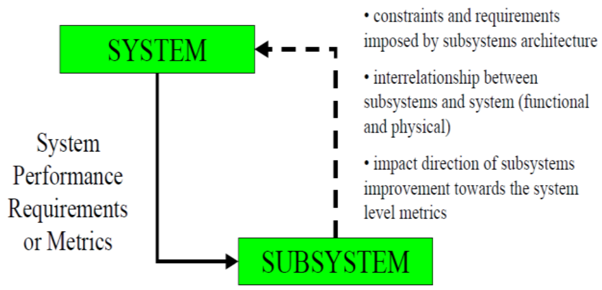

Figure 3. Functional relationship between aircraft system and its subsystems

The imposing functional relationship between the aircraft system level and its subsystems level is depicted in Fig. 3. As mentioned, the required aircraft system capability will be the determining factor of the incorporated subsystems functions and this is represented by the solid arrow in Fig. 3. As for the dotted arrow in Fig. 3, it indicates the constraints or feedbacks from the functional subsystems level back to the upper system level. This return loop includes the existing interrelationship between the subsystems that may impact the system from both physical and functional scopes. For instance, to enable the aircraft to fly, it will require adequate thrust that is supplied by the power plant subsystem. However, in order for the power plant to be operative, it also needs electrical power (for engine starting) and fuel. This shows functional dependency between the subsystems, which means that all the related subsystems must co-exist in the design to achieve that particular aircraft system level function. In the bigger picture, this also imposes design architecture and physical constraints whereby all these subsystems must be inter-linked together and their locations within the design are subjected to design compromises.

To investigate and identify all relationships in between all subsystems or between the subsystems and the aircraft system level, the aircraft level functions need to be broken down into their lower level functions. The decomposition process of the functions is done up to the stage where they are conveniently linked to the subsystems level at which the physical decisions are made to ensure a high accuracy in the functional mapping of the aircraft. Aircraft functions are mainly derived from the corresponding requirements of the four primary phases during its flight mission: pre-flight, take-off, flight and post-landing operations. According to [5], more detailed sub-functions of these four high-level tasks can be identified as shown in Fig. 4. In this case, the primary functions are decomposed into 12 sub-functions and it should be noted that to achieve some of the primary functions, more than one sub-function might need to be simultaneously executed. For instance, for a successful take-off preparation, aircraft must be able to move smoothly on the ground to its take-off position (carriage, braking and steering function). Additionally, it must be able to receive the signal from airport control tower (communications function).

It could be observed that the 12 sub-functions are still too generic to be at the subsystems level. This means that they can be further broken down into smaller or lower-level functions. The sustainment function refers to both scheduled and also unscheduled maintenance, whereby every aircraft is subjected to scheduled maintenance and servicing operations depending on the operating life of its parts and components. In designing an aircraft, its adaptability to this pre-flight operation is often taken into account in order to save time and cost. Saving the down-time for an aircraft means that it can be used in a higher utilization mode. Before the aircraft is airborne, it will need to perform several ground tasks, which include the ability for a smooth ground movement. This movement involves carriage capability, as the aircraft needs to carry all its onboard loads and allows the pilots to have adequate control of its ground heading through braking and steering functions. The braking function is very important particularly for the landing phase. Upon touchdown, the aircraft is still at a rather high velocity and therefore, it is vital that application of the brakes helps to slow it down within the allocated landing field length. This function becomes equally important during the take-off phase whenever emergency take-off abortion takes place. As for the steering function, it allows the pilots to turn the aircraft in the desired direction during ground maneuvers.

The aircraft must generate good aerodynamic performance. In a more descriptive term, this corresponds to the generation of high lift and low drag forces. The lift forces will help to get the aircraft airborne and climb to the desired cruise altitude, while at the same it also has to minimize the drag generation. In addition, thrust is needed for the aircraft to fly forward and to counter the drag forces. Apart from that, the secondary use of this force can be applied during landing roll. The reversed thrust, along with drag forces, can help slow down the aircraft. The propulsion segment mainly produces thrust and, as much as it is preferable to have a high thrust producing capability for higher aircraft forward speed, this can also come with a bigger and heavier aircraft engine.

The reason behind the operation of a commercial transport aircraft is to transport passengers (and cargo) from one place to another. Thus, the aircraft design must be able to provide crew and passenger accommodation. This includes adequate space for crew and passenger seating, suitable in-flight cabin environment, plus maybe some entertainment facilities. This function is one of the criteria that differentiate an aircraft from its competitors, or to some extent creates comparison between airlines. In addition to crew and passengers, the aircraft is also designed to transport cargo. Although cargo transportation for most commercial transport aircraft is considered secondary to passengers, the design still need to provide adequate space for in-flight cargo storage and ability for loading and unloading access. Moreover, since the aircraft operation is performed at high altitudes where the environmental condition is not really suitable for normal human survival since low environmental pressure creates difficulties in human breathing process and very low temperature presents danger to normal human body operation. To enable transportation of people, artificial cabin environment must be provided to suit human body condition. The environmental control is also required to protect aircraft from its operational surroundings as extreme environmental conditions can subject the aircraft to potential damages and operational danger.

Another important function to enable the aircraft to operate within the available airspace in safe and systematic order is the communication function. The pilots exchange information with the control tower, another aircraft, or other ground nodes using the external communications means. On the other hand, provision of internal communication links allows the pilots to communicate with other crew members or for crew members to communicate with the ground crew while the aircraft is still on ground. This function allows the pilot to be more aware of the current situation in the aircraft cabin area and able to take swift precaution measures in case of any emergency. Another task related to the aircraft functions is to provide guidance and navigation. This function is linked to provision of necessary navigational information for the pilot to fly the aircraft. A safe flight operation is dependent on the accuracy of navigational data provided to pilots since their decisions during flight are based on these data.

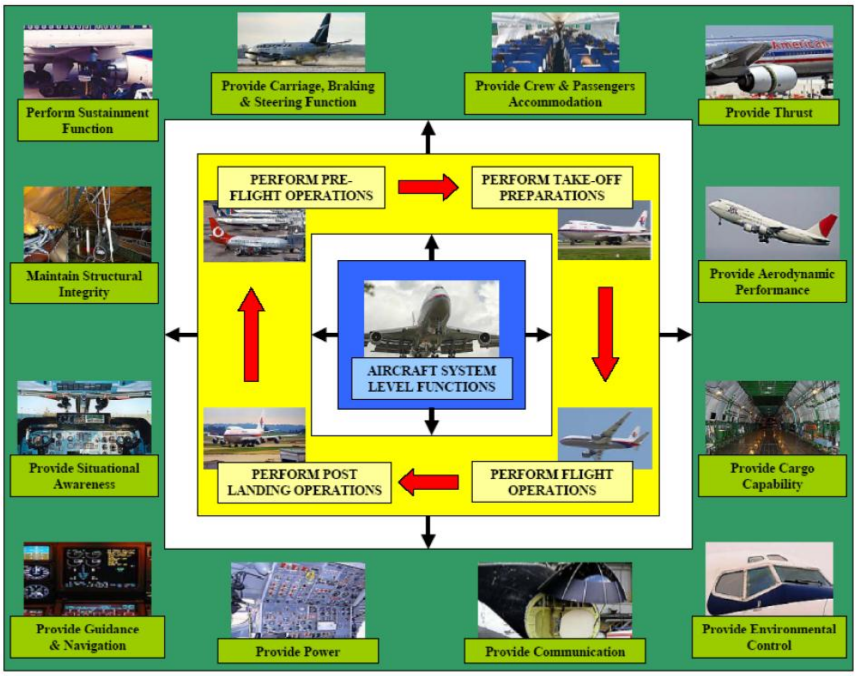

Figure 4. Functional decomposition of aircraft system.

The operation of aircraft subsystems is subjected to power supply since they will need adequate power to operate. This condition leads to the next function, which is the provision of power. Note that for any aircraft system, there are mainly three different kinds of power supply that are used: Electrical power, pneumatic power and hydraulic power. The electrical power is supplied from its main source to the subsystems via the electrical wirings. On the other hand, the pneumatic power is linked to the use of air pressure to perform mechanical work while the hydraulic power is associated with the conversion of hydraulic fluid pressure into mechanical work.

Another function for the aircraft is to provide situational awareness, which is important in detecting flaws throughout the flight operation. As the aircraft designs become more and more complex, manual monitoring of subsystems operation can be very tedious for the pilots. By having this capability, the crew will be provided with enough information in terms of subsystems operational conditions to fly the aircraft safely. In addition to subsystems monitoring, situational awareness also includes the observation of external conditions of the aircraft. Although this external monitoring is usually covered by data from the guidance and navigation function, the pilots should be able to conduct simple manual navigational tasks in case of flight navigational computers failure.

Lastly, the final function associated with the aircraft system is to maintain its structural integrity. This function addresses the capability of the aircraft to sustain any loads applied on it throughout its operation such as the aerodynamic, inertial and pressure loads. The aircraft also must be able to counter any internally applied loads such as the pressure conditions inside the cabin, which is necessary to suit the occupancy of the crew and passengers.

Based on the previous discussion, the aircraft system level functions can be further broken down into several lower level functions. By having these functions at their lower level, it will be a much easier task to address the functional aspect of aircraft subsystems and link to the physical design realization. Table I summarizes the breakdown of these functions.

III. PHYSICAL DESIGN MANIFESTATION

One of the objectives of product conceptual design stage is to develop physical design solution that can fulfill all of the required functions. In order to derive the design concept from functional approach, the designer needs to explore, define and organize the functional structure of the design. As the product is designed for a particular purpose or mission, the function of its components or parts, either independently or together as an interrelated assembly, should enable it to achieve the latter. In other words, the purpose or the mission of the product can be further decomposed into some hierarchical sub-functions that will support its attainment, such as the one highlighted in the previous section for an aircraft system.

TABLE I. FUNCTIONAL BREAKDOWN OF THE AIRCRAFT

Aircraft System Level Function	**Primary Function Breakdown**	**Secondary Function Breakdown**
Perform Pre-Flight Operations	Perform Sustainment Function	• Provide Servicing Capability • Provide Maintenance Capability
Perform Takeoff Preparations & Perform Post-Landing Operations	Provide Carriage, Braking, and Steering Function	• Provide Carriage Performance • Provide Braking Performance • Provide Steering Performance
Perform Flight Operations	Provide Aerodynamic Performance Function	• Provide Lift Performance • Provide Drag Performance • Provide Stability • Provide Aerodynamic Control
	Provide Thrust Function	• Provide Forward Thrust • Provide Reverse Thrust
	Provide Crew and Passenger Accommodations Function	• Provide Crew and Passenger Space • Provide Seating • Provide Storage • Provide Galley Accommodations • Provide Lavatory Accommodations • Provide Entertainment
	Provide Cargo Capability Function	• Provide Cargo Space • Provide Cargo Loading/Unloading
	Provide Environmental Control Function	• Provide Air Conditioning • Provide Pressurization • Provide Oxygen • Provide Ice Protection • Provide Rain Protection
	Provide Communications Function	• Provide External Communications • Provide Internal Communications
	Provide Guidance and Navigation Function	• Determine Location of Aircraft • Determine Attitude of Aircraft • Determine Speed of Aircraft • Determine Direction of Aircraft • Provide Flight Management
	Provide Power Function	• Provide Electrical Power • Provide Hydraulic Power • Provide Pneumatic Power
	Provide Situational Awareness Function	• Monitor Aircraft Status • Provide External Awareness
	Maintain Structural Integrity Function	• Sustain Loads • Maintain Pressure

For many aircraft manufacturers, it is very common to have suppliers for the subsystems but they need to define the design specifications for the subsystems. For functional breakdown, it makes sense to stop at the level where the decisions on the physical subsystems are made. There is no need to proceed further into much detailed level like up to the "bolts and nuts" since the supplier is responsible for the detailed design of the subsystem. Overall, it can be said that the lowest level of the functional tree will depend on the level where physical design decisions are made by the manufacturers. If the manufacturer produces from scratch by itself, then the breakdown needs to be made up to the smallest details of the product design.

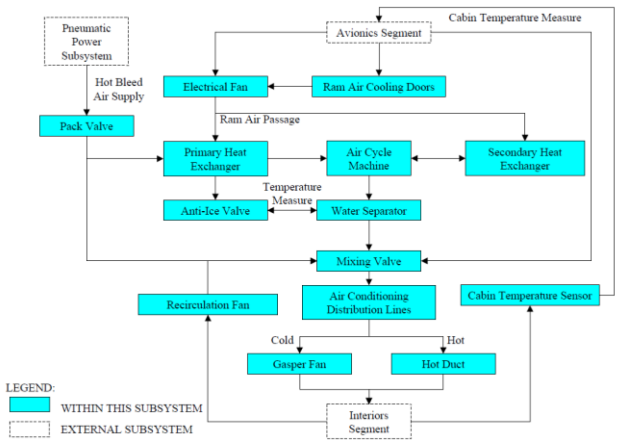

Figure 5. Physical subsystem build-up for "provide air conditioning" function.

Once the functional breakdown tree is completed, each of the lowest level sub-function that has been identified can be translated into their physical realization. An example is shown in Fig. 5 for "provide air conditioning" sub-function. It can be observed that once the physical composition of the subsystem is defined, the required functional interrelationships between the different subsystems can be identified and mapped out. In this case, the electrical fan needs electrical power input and thus a functional interlink to the avionics segment is created to satisfy this requirement (i.e. electrical switches to control the electrical power input from the electrical power subsystem). The designer can also opt to change the physical architecture of the aircraft by deciding a different functional link for the air conditioning fan. Let's say instead of using electrical fan, the designer decided to use a mechanical-driven fan. Hence the physical architecture of the aircraft will change in the sense that there is no longer a need to connect the air conditioning subsystem to the electrical power subsystem but a new need is created to have a link to the propulsion subsystem, where the mechanical input is used to operate the fan. This highlights the powerful impact of changing the functional interdependencies to the overall physical architecture of the system.

IV. Conclusion

In this paper, the main objective is to highlight the potential of deriving the conceptual product design through functional analysis. As opposed to having a physical fixation on how a product design should be during conceptual stage, exploring the product's functional space provides more design freedom and appears to promote more innovative ideas, especially for complex product such as an aircraft where the dynamics of the functional interrelationships between its subsystems is of high level. This realization creates an interest and also a need for a conceptual design methodology that can assist in streamlining the process for designers. It is the intended future work from this study to develop such conceptual design methodology for use in complex product design and development.

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