A Systems Engineering Hackathon - A Methodology Involving Multiple Stakeholders to Progress Conceptual Design of a Complex Engineered Product

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ABSTRACT This paper describes a novel hackathon-style system engineering process and its value as an agile approach to the rapid generation and development of early design concepts of complex engineered products–in this case a future aircraft. Complex product design typically requires a diverse range of stakeholders to arrive at a consensus of key decision criteria and design factors, which requires effective articulation and communication of information across traditional engineering and operational disciplines. The application of the methodology is highlighted by means of a case study inspired by Airbus where stakeholder involvement and internal collaboration among team members were essential to achieve a set of agreed goals. This paper shows that a hackathon grounded on systems engineering approaches and structured around the technical functions within an engineering company has the capability and capacity to communicate a coherent vision and rationale for the conceptual design of a complex engineered product. The hackathon method offers significant benefits to these stakeholders to better manage, prioritize, and decrease excessive complexities in the overall design process. A significant benefit of this agile process is that it can achieve useful results in a very short timeframe (i.e., 80% reduction), where it could take up to a year to accomplish compared with using current/regular internal methods.

INDEX TERMS Complex systems engineering, design engineering, hackathon, modeling and simulation, product design, systems architecture, systems process modeling.

I. INTRODUCTION

The design of highly complex products is an iterative process comprising complex executive engineering processes, balancing challenging customer requirements, technical decisions and manufacturing decisions all set against a cost/performance trade-off analysis. Throughout the process a wide range of stakeholder's views, across the product lifecycle must be considered in order to reach a consensus for the final design which has to be set against market factors such as product positioning, competitiveness, need and many other factors [1]. During the design process, important decisions are required that span technical design, marketing, manufacturing and product lifecycle and organizational considerations. In the case of a new product, where the market need is speculative, then the design concept must provide a convincing case if it is to proceed to the manufacturing stage.

Systems engineering has evolved over the past three decades as a fundamental design and development process for engineering complex products [2]. Typically, the development model necessitates a fixed early definition, or concept of operation, of the product, system or services that are to be built. At this conceptual stage there are many factors that need to be considered and it is necessary to get a wide range of stakeholder buy-in. It is essential that each stakeholder has a shared vision of the product and what factors are critical to its eventual realization. Stakeholders may also have different or conflicting requirements that need to be fully explored early in the process. Consequently, it is crucial to spend time developing a robust conceptualized product, particularly

when it needs to be positioned within a highly competitive market place, as market drivers need to be included in the early decision making process [3], [4]. If the timeframe from product conceptualization to implementation is more than a few years, then the conceptual design must include a certain amount of prediction in terms of the market trajectory/viability and likely technology options. It is therefore necessary to bring stakeholders together early to share collective technical knowledge and make important technology decisions, encapsulated in a conceptual design model, which can be communicated across the wider stakeholder community.

The conceptual design model aims to define several candidate system architectures that have the potential for achieving a viable product. The success of the procedure relies on review and revision of the results by engineers, analysts, clients, experts' elicitation, and other project stakeholders. Only through several stages of review and revision can the final result be finalized into a viable product [5]. There are numerous methodologies to evolve a design, but for highly complex products such as aircraft, ships and trains these processes and review stages can take months or even years. This research aims to address this problem by exploring an alternative method to speed up the early conceptual design phase and condense the review stages of complex engineered products.

A. BRAIN STORMING VERSUS THE HACKATHON PROCESS

During design review stages, the goals and constraints of the various stakeholders can sometimes be in conflict and a process of negotiation must be used to reach agreement, which of course takes time. Brainstorming is a common technique to capture ideas in a structured way against logically defined headings. Brainstorming can be used to flush out options, but this is essentially a process whereby all ideas (good and bad) are captured and clustered/categorized. The aim of a brainstorming session is to reach a consensus on a set of recommendations or a static representation of ideas or agreements. However, in the case of a complex product there is a need to delve much deeper and further into the technical detail than simply creating a list of recommendations.

Hackathons are a relatively new process and have been used successfully to bring disparate teams of computer programmers together face-to-face to create, in a semi-adhoc manner, working implementable code. The hackathon event tends to be semi-structured and is driven by a set of top level goals. It is the fluidity of the interaction between hackathon members (who take on specific roles) that brings about very rapid and iterative code generation. The nature of the interactions between participants is of interest to the authors, and the achievement of shared understanding and time reduction that arises through co-location of decision makers.

B. RESEARCH AIM

The aim of this research was to explore the concept and usefulness of a hackathon-style process during the requirements

and conceptual design phase of a complex engineered system. Below are the research questions to answer (RQ).

RQ1) What is the value of a hackathon, as part of an accelerated multi-discipline decision making process improve decision-making and consensus of agreement in a large complex project?

RQ2) What is the added value of conducting a hackathon event in the quest for effective and efficient system design?

C. METHODOLOGY

Initially, an investigation of the hackathon event was undertaken to ascertain advantages and disadvantages of the approach. The researchers then collaborated with Airbus, a European multinational corporation that designs, manufactures and sells civil and military aeronautical products worldwide. A multi-day 'Systems Engineering Hackathon' event was held. The purpose of the hackathon was to simulate the conceptual design of a complex engineered hypothetical future aircraft, namely the Agile Wing Integration (AWI) project, which arguably represents one of the most demanding technical engineering challenges today because of the sheer number of decisions that have to be made across multiple domains. Hypothetical project and customer stakeholders were invited from industry, research organizations and academia.

The hackathon event covered the entire conceptual design process of an aircraft looking at different wing technologies, with the goal of being able to recommend a fleet allocation to an airline – "Airline A" – based on operating costs. The time constraint imposed by the hackathon process could pose a challenge in allowing for design considerations to be made in conjunction with decisions about what technology should be used to meet customer needs, against many conflicting market demands. Coupled with this is the need to deliver products that meets the market needs in terms of safety, operating cost, compliance with regulations, profit generation, lifespan whilst still being competitive in an increasingly tough and evolving market [6], [7].

The research objective therefore, was to understand the relative importance of different stakeholder goals and how they need to be considered in the context of a trade-space (aka design space exploration) activity as part of a fast-evolutionary aircraft conceptual design process.

This paper presents an exemplar case study reporting on both the outputs and outcomes of the hackathon and makes a case for the value they bring in reaching a consensus in a time efficient manner, and in overriding complexity challenges associated with the design phase of complex systems. A significant output from the hackathon was an executable blueprint that enabled trade studies to be performed on the different design solutions to provide new insights. The paper discusses how the real value of creating the executable blueprint in an iterative manner has significant utility since it not only helps balance out the required design capabilities, but it actually brings about a shared understanding of the

decision-making process of the stakeholders and also highlights where the design needs to be relaxed or optimized.

II. ADVANTAGES AND DISADVANTAGES OF HACKATHONS

Hackathons were originally initiated as events wherein programmers and in software designers collaborate intensely on software projects. "The word hackathon is combined from the words hack and marathon, where hack is used in the sense of exploratory and investigative programming" [8]. Hackathons usually last from one day up to a week. The motivation behind hackathons can be educational or social and in many cases the goal is to create usable software. Hackathons mainly have an explicit theme, for example: a programming language, an application or an application interface, a specific subject or a demographic group of the programmers. In other cases there is no restriction on the type of software being created [9]. Hackathons are not only used in software or hardware development, they have been employed in numerous domains such as: aviation industry [10], governmental, education [11] and healthcare [12].

In general, hackathons have no boundaries in terms of focusing on a specific problem or participants, providing the aim is to rapidly generate software applications. Though, the variety of hackathons can be categorized as tech-centric or focus-centric. Tech-centric hackathons concentrate on software development with a specific technology or application. Focus-centric hackathons' objectives are to develop software to tackle or support social problems or a business matter, recognized as applied hackathons [5]. Examples of successful hackathons include the Facebook 'like' button [13] and the mobile application GroupMe [14].

Hackathons support a collaborative co-development process similar to co-design [15], also referred to as participatory design, and BarCamp [16], which is primarily concerned with the early design phases of software applications. However, systems engineering hackathons as proposed herein, focus on the integration of stakeholders and their respective models, and the in-depth collaboration amongst heterogeneous partners in the exploratory and design phases of a product.

There are multiple desirable features and themes incorporated into a hackathon event [17]. Defined processes aim to deliver goals set by the hackathon organizers. Some of these can be summarized as:

- Focused study and face-to-face stakeholder communication
- To gain a better understanding of how different teams can work together towards a single aim
- To determine and overcome problems
- To synergistically push the boundaries of existing knowledge
- Enhanced solution iteration in the sense that prototypes and simulations result that incorporate the features defined by the stakeholders in an executable form so that "what if" scenarios can be performed.

A. ADVANTAGES OF HACKATHONS
There are many advantages of a hackathon event:

- Quick results
- Creative process with a real-world grounding.
- Team engagement: different team members get the opportunity to know each other and their roles in the project
- Develop a shared understanding
- Learn and earn new skills.

B. DISADVANTAGES OF HACKATHONS
There can be a few drawbacks to hackathons:

- Loss of effort on other projects while attending the hackathon
- Lack of individual focus due to the number of people involved
- Unusable outputs like code or data
- Exhaustion
- Intensive and therefore unsustainable on a regular basis.

III. THE AIRBUS SYSTEMS ENGINEERING HACKATHON
The Airbus Systems Engineering Hackathon was specifically focused on rapid iteration of future aircraft concepts by including all the processes and internal stakeholders involved in a product's creation albeit at a reasonably high level of abstraction. A week-long hackathon event was run in January of 2016, at Airbus in Bristol (U.K.), to tackle a complex multi-criteria decision-making problem. The specific goals of the hackathon for Airbus were as follows:

- To develop a framework for future aircraft concepts of operations
- Bringing all the partners working on different aspects of the project (some of whom were internal groups in Airbus and external AWI project partners) to the same level of understanding on the scope of the project.
- Agree appropriate levels of granularity of analysis for each modelling activity
- Build a common understanding and degree of familiarisation with conceptual aircraft design processes
- Develop other wing design topics of commercial interest.

The goals of the Airbus hackathon align well with Systems Engineering as a practice: an interdisciplinary approach that enables the successful realization of operational systems that satisfy customer needs and other stakeholder requirements. This intense short-term investment in time, to solve a problem and to align all stakeholders with one common goal, is a new process in an Airbus systems engineering project.

The benefit of a hackathon is that stakeholders are in the same location, which allows for the elicitation, discussion and refinement of each of the stakeholder's expectations and permits efficient collaboration during subsequent tasks. Stakeholder interactions for the AWI Project hackathon is shown in Figure 1. The primary interaction was between the Original Equipment Manufacturer (OEM i.e. Airbus) and a
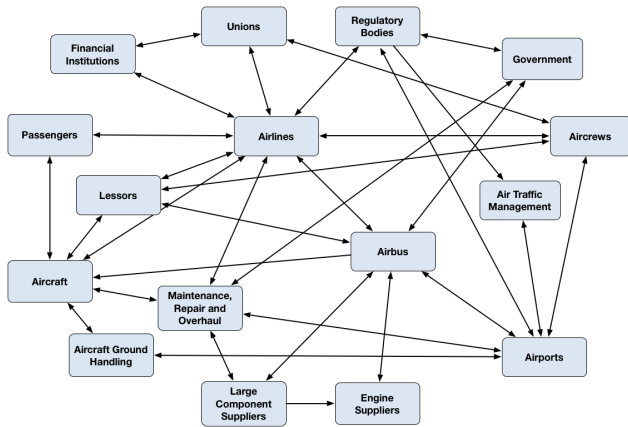
fictitious European airline - "Airline A". However, in this case, Airbus staff (product, policy makers, architects) played the role of the Airline A's stakeholders and generic airline data was made available to model the aspects of interest.

IV. THE DESIGN SCENARIO

The scenario used in the hackathon was for an Agile Wing Integration (AWI) project. The assumption was made that the aircraft type should be of a modular design. Modularity [18], [19] in this context refers to the design of a system where different components can attach to the same product platform but can achieve different functions. Alternatively, commonality implies the same component can attach to different products to achieve the same function [7].

The purpose of a modular aircraft design is to be able to change the components (modules) of the aircraft based on adapting to changing demands in the future, such as seasonal variations affecting passenger numbers (i.e. seats offered by the airline) or route churn, potentially affecting the range capability of an aircraft. Modular aircraft cannot be designed effectively on a single aircraft type, this is illogical from a design and economic perspective. Also, the Top-Level Aircraft Requirements (TLARs) setting for modularity has to be based on routes and fleets, rather than on single design points [20]. Aircraft designed from fleet level TLARs are targeted at an airline's point of interest, in order to offer the best potential options. The aircraft manufacturer's point of view on risk and opportunity has to be considered too and combined with the airline's goals.

The design objective of the hackathon was to propose a fleet with modular technology for Airline A's operations for today's market until 2020. For example, suppose Airline A had a current demand that requires 100 aircraft from the short-range family (for short haul flights), 55 from the medium range family (for medium haul flights) and 12 from the long-range family (for long haul flights). The hackathon objective is to propose the type of aircraft and the numbers required in 2020. The future plans must take into account various factors, such as increasing fuel and labor costs, or economic

instability in Europe, which might lead to less air transport demand or conversely higher propensity to travel, which will result in higher air transport demand. At the end of the event it was expected to be able to estimate fleet level savings using modular aircraft configurations and identification of the most resilient and robust current/future fleet solutions for the Chief Executive Officer of Airline A.

V. STAKEHOLDER ROLES AND THE HACKATHON PROCESS

Before the hackathon began, Airbus identified the internal and external stakeholders (i.e. the customer) who would be involved in the hackathon event. Internal stakeholders were grouped into three teams: marketing, engineering and architecture. Airbus staff who were highly experienced in how airline customers operate their business, took the role of Airline A - the fictitious customer.

The hackathon event was deliberately designed to allow for iterative design and development activities. The phases of the process included information acquisition, concept generation, design and modelling, analysis and evaluation. Figure 2 illustrates the top-level process flow of the hackathon with details of each stakeholder.
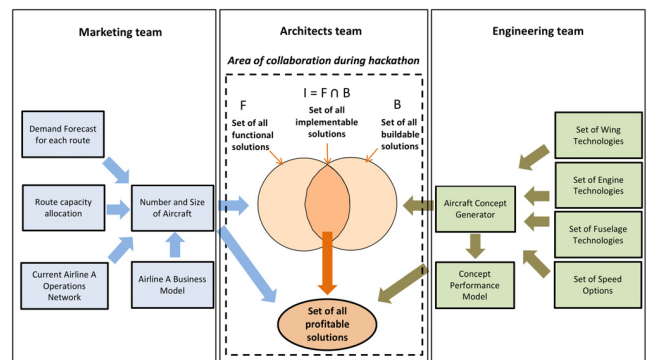

FIGURE 2. AWI hackathon process flow.

A. THE MARKETING TEAM

The marketing team's involvement started prior to the conceptual design phase but they were also closely involved in the design and modelling phases. The team was tasked with understanding Airline A's value proposition to its passengers and to propose solutions that might add value to their business. Solutions should be a set of functions or processes, for example: possible size of aircraft to deploy on various routes (155-seater aircraft on route A, 189-seater aircraft on route B), estimation of ticket prices, or the proposed cost structure of the airline. Solutions had to be independent of any technology.

To begin, the marketing team received fleet operations and business data from Airline A. They studied the market examining how it evolves over time and the best ways of meeting the demand with minimal usage of capital assets. For this, they had to study the customer's business, and create

revenue and cost models. These cost and revenue models were later used by the architecture team to rank the solutions based on their profit generating capability.

B. THE ENGINEERING TEAM

The engineering team's main contribution was during the conceptual design phase, more specifically in aircraft sizing. The team was responsible for creating technical solutions based on a set of modular technologies available for various aircraft components such as wings and fuselages. The goal was to define a set of viable and buildable solutions that satisfied Airline A's requirements.

Aircraft concepts were generated from a technology portfolio, which needed minimal input from other stakeholders, however all other teams were dependent on their outputs. This involved creating a full factorial combination of technology options for major aircraft modular components such as fuselage, wing, engine in conjunction with applying a cross consistency assessment check to reduce and validate the solution space. A set of buildable concepts were defined, which included sizing rules and fuel burn performance for a set of given mission ranges. The outputs from the engineering team were made available to the architecture team.

C. THE ARCHITECTURE TEAM

The primary role of the architecture team (comprised predominantly of engineers from Airbus) was to propose the final solution to Airline A. They were involved in most of the project phases: conceptual generation, design and modelling, analysis and evaluation. Furthermore, they were the key correspondent amongst other teams, which enabled efficient and accurate data handling between stakeholders.

The intersection set of functional solutions from the marketing team and the buildable (technical) solutions from the engineering team established the design space for the architecture team. Each concept generated had to be sized so that the aircraft would fulfil the routes and aircraft capacity requirements derived from the marketing team.

Once the aircraft was sized the architecture team used the performance data generated by the engineering team to create a surrogate model for determining the fuel burn for a particular route. This was a vital input to the cost model that was created by the marketing team. The architecture team was able to rank the solutions in order of merit, based on the profitability criteria for Airline A, by generating data for all routes in the network and entire fleet.

The architecture team had to also consider the engineering viability of these solutions from an OEM manufacturing perspective. For sustainable growth the chosen solutions had to be profitable for Airline A as well as cost effective for the OEM. The final set of solutions were passed on to the overall aircraft design (OAD) experts for further analysis.

D. THE CUSTOMER – AIRLINE A

In the hackathon scenario Airline A is a major customer and therefore has a significant influence on the aircraft manufacturer's propositions and design solutions. Airline A had detailed requirements for their specific fleets to be taken into consideration during the hackathon. Understandably, the airline's focus was on the lifecycle cost of the aircraft comprising: purchase or lease price, direct operating cost, maintenance costs, fuel efficiency, aircraft size (such as weight, seating or cargo capacity and payload), component maintenance and spare parts. Consequently, they played a major role in shaping proposals from the OEM.

E. STAKEHOLDER COLLABORATION

Prior to the hackathon the team leaders from the respective groups defined the expected outcomes of the event and what will 'good look like'. Furthermore, day-to-day expectations were outlined for each team to allow for systematic progress to meet the intended outcomes. The architecture team had the main negotiating role, since they had the additional responsibility of interacting between other teams and bringing the whole process together (for hackathon purposes only) and producing a set of final results. However, all stakeholders were critical due to their major interactions. Members of the architecture team had frequent discussions with both the engineering team and the marketing team to exchange data and information in order to create the model integration frameworks. The collaboration was straightforward in critical process phases, although the time was very limited. Conversely, delays in delivering results due to software or calculation issues from one team to another occasionally posed a challenge in stakeholders' collaboration as one team's progress was dependent on data resulting from another team.

Stakeholder collaboration worked remarkably well, and a viable set of final solutions were achieved in a short space of time. It was evident to see a great deal of knowledge exchange taking place and a general understanding being built beyond the process outlined at the beginning of the hackathon event.

VI. THE HACKATHON EVENT – ACTIVITIES AND OUTPUTS

This section describes the models generated by each stakeholder team in more detail.

The architecture team were tasked with generating the architecture of the whole hackathon process and the computational framework for all teams to feed their respective data inputs into. Each of the model outputs (passenger demand, number of flights, fleet allocation, costs, performance, concept generator) were captured in a master Excel spreadsheet. This allowed for seamless data integration amongst different teams. The architecting process result can be seen in Figure 3 with each box representing the models created by all teams. These models were a result of stakeholder discussions and from the skill set of the participants. These models were as follows:

- Marketing team's models
  - Airline Demand Model
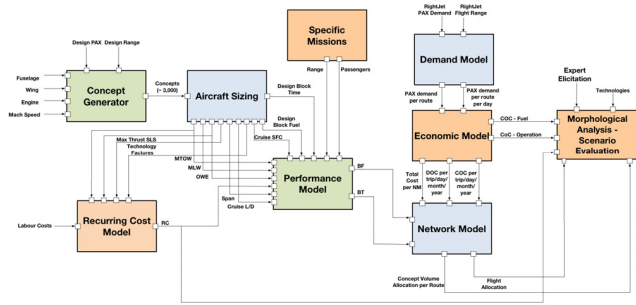 - Economic Model
  - Network Model

FIGURE 3. The AWI hackathon architecture.

- Architecture team's models
  - Specific Missions Generator
  - Recurring Cost Model (Surrogate)
  - Performance Model (Surrogate)
- Engineering team's models
  - Concept Generator
  - Aircraft Sizing
- Final Results: Morphological Analysis and Expert Elicitation.

The hackathon process was defined and the role of each stakeholder or engineering team was articulated through the model-integration architecture shown in Figure 3. Generating an integration architecture allows for details to be captured and made available to different teams. These details include; model types and data types; model owner and responsibility; data transfers between model owners based on input/output specifications; and sequencing of modelling and data analytic activities.

A. THE MARKETING TEAM'S MODELS

The marketing team was responsible for designing the Airline Demand, Network and Economy Models.

1) AIRLINE DEMAND MODEL

The marketing team reviewed the annual business reports of Airline A and analyzed the fleet operations data (passenger demand and flight range). This helped to forecast the passenger demand on each route and number of flights available per day, creating a Demand Model.

2) ECONOMY MODEL

The main outputs of the Economic Model were Cash Operating Costs (COC). The COC are the costs the airline pays for flying the aircraft from one point to another including: fuel costs, maintenance costs for the aircraft, engine, crew costs, landing fees, navigation charges, etc. Direct Operating Costs (DOC) [21] are the operational costs per flight and is the sum of fixed and variable costs including: depreciation, insurance, interest, fuel, ground services, flight and cabin crew, etc.

3) NETWORK MODEL

The Network Model was designed to optimize the allocation of different configurations to each route via the fleet allocation and demand per route. This model determined fleet allocation and concept quantity allocation per route.

B. THE ARCHITECTURE TEAM'S MODELS

The architecture team designed the Concept Generator, Specific Mission Generator, Recurring Cost Model and surrogate Performance Model. Subsections below describe the generators and models in more details.

1) SPECIFIC MISSION GENERATOR

Two factors were considered to generate specific missions: payload and range. A chart was created to aid designers choose payload and range design points for assessment using the city pair and passenger demand dataset provided by Airline A. This was achieved by acquiring minimum and maximum distances between city pairs and passenger numbers from the above-mentioned dataset. The output data from this mission generator combined with the aircraft sizing data provided by the engineering team and was used late for calculations in the surrogate Performance Model.

2) RECURRING COST MODEL

The Recurring Cost Model was designed and implemented to estimate the cost of manufacturing an aircraft based on labor costs (a constant number was assumed) and aircraft configuration data generated by the Aircraft Sizing block. The recurring cost score was taken as the relative ranking of the recurring cost per passenger count (PAX) of each aircraft configuration at the maximum payload and maximum range design point.

3) PERFORMANCE MODEL

In conventional aircraft design the use of new technologies must preferably be accompanied by a decrease in aircraft weight and drag - the two most significant design drivers in traditional analysis - bringing a fuel burn efficiency improvement for a spot design mission. In order to calculate the proposed fleet-level fuel burn efficiency and estimate how much fuel is to be carried by each aircraft, the surrogate Performance Model was built to calculate Block Time and Block Fuel for Airline A's specific route network. These outputs were used later in the process by the Economic Model implemented by the marketing team.

The architecture team managed the data collection and data exchange amongst other hackathon teams to form the master data spreadsheet. This spreadsheet was required by all stakeholders since the hackathon generated large amounts of data to be handled.As a part of this process, data integration evolved continuously, which was a computationally costly exercise in terms of data formatting. The data gathered from all internal stakeholders was then translated into

a standardized template - a Master Data Spreadsheet - and formatted to fit the calculations during the process.

C. THE ENGINEERING TEAM'S MODELS

The engineering team undertook aircraft sizing, which is one the most important stages in aircraft design as these parameters determine the overall performance of an aircraft. The details of the aircraft sizing process are discussed in the following sub sections.

1) CONCEPT GENERATOR

Initially the architecture team generated a combination of all possible concepts using four different component types. After cross consistency assessment by Airbus experts the reduced set of concept solutions were passed on to the architecture team.

2) AIRCRAFT SIZING

Aircraft sizing is the process used to predict the change in capability, performance, manufacturing cost and revenue for an aircraft combination for a given design range. As part of this process the team came up with baseline aircraft performance estimates as a surrogate model based on spot design points and baseline concepts. Using in-house aircraft performance software, the engineering team calculated aircraft performance measures for each feasible concept based on changes in the mission design point (PAX/Range/Mach) and technologies used. They applied weighting and scaling factors to Lift versus Drag (L/D), Maximum Weight Empty (MWE) and Specific fuel consumption (SFC) values. Baseline aircraft performance was defined as weight/delta drag vs range, and baseline concept capability was defined as PAX vs MWE.

The design range and payload capability of an aircraft is a critical part of aircraft sizing that is assessed using payload range diagrams to specify the limiting operational envelope of an aircraft. This diagram was used to estimate where different aircraft variants could fit and check overall feasibility of configurations versus actual mission requirements. The payload denotes all the mass that can be carried by an aircraft excluding fuel. The longer the range, the more payload must be forgone for fuel. Many aircraft are operated significantly below their design ranges. The longer the design range the more flexibility the aircraft has to meet the needs of multiple airlines however, this may mean the aircraft is carrying around redundant capability when this is not required (i.e. the aircraft is over-engineered for what it is being used for).

The design capability chosen for an aircraft sets a hard boundary for its ability to operate in the market. The result generated from the hackathon process were the top twenty configurations resulting from the morphological analysis, which combined the suitability of the aircraft design from a performance perspective with the technical and manufacturability constraints approximated by expert elicitation. These results would later be incorporated into a dynamic executable simulation model.

D. FINAL RESULTS: FLEET ALLOCATION, MORPHOLOGICAL ANALYSIS AND EXPERT ELICITATION

For the final stage of the hackathon the output data was gathered in a comprehensive Master Data Spreadsheet for subsequent analysis. For this purpose, the top twenty configurations were determined from the fleet allocation model. Followed by morphological analysis [22], which represented the expected cost and benefit to Airbus based on cost modelling of different concepts. Experts could then derive specific designs to propose to the customer.

The top twenty represented the preferred concepts from Airbus' perspective. Figure 4 illustrates the output of the fleet allocation activity, which included the design capacity of the PAX (family) option and the how many (frequency) of each capacity (family) were needed to meet the demand in the given airline network. The frequency refers to the number of aircraft required for each PAX capacity. Results were selected based on the 2015 economic models and assumptions retrieved from the annual business reports of airlines and the values which best-suited Airline A's existing network and daily flight schedules.
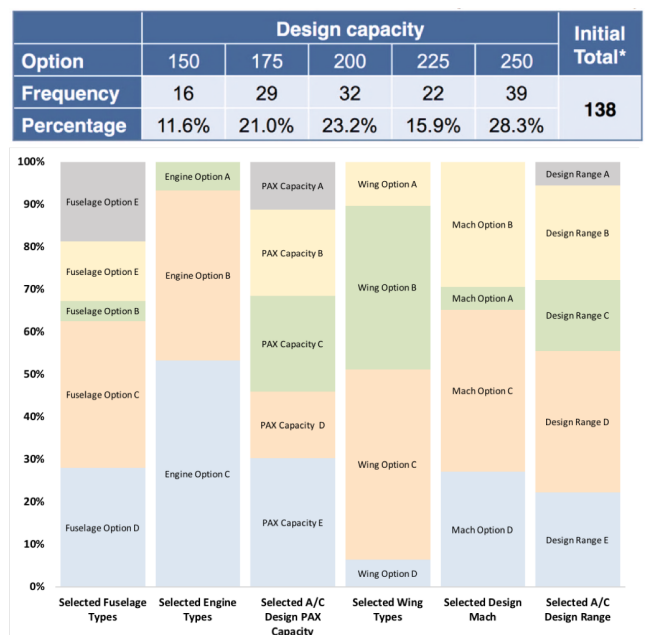

Option	Design capacity					Initial Total*
	150	175	200	225	250	
Frequency	16	29	32	22	39	138
Percentage	11.6%	21.0%	23.2%	15.9%	28.3%	

FIGURE 4. Number of aircraft required for current "airline A" network.

The graphs shown in Figure 4 – the bottom charts indicate each component by predominant usage by Airline A. For example, in Selected Fuselage Types, Fuselage Options C is the most significant used, flowed by Option D, E, A and B.

The results of the morphological analysis [22] generated a ranked assessment of concepts based upon specific Key Performance Indicators (KPI). Typically, for any aircraft technology these KPI's would include the qualitatively-assessed impact of the technology (if any) on aircraft weight and aircraft drag. They would also include financial or resource

costs such as procurement, maintainability, ease of repair, ease of installation and manufacture. Each of the KPI's would be ranked in importance (with corresponding weightings) for a specific application. Ultimately this task helped to refine the optimal technology choice.

Morphological analysis enabled assessment of all possible configuration combinations for different operational scenarios against a selection of design criteria. The assessment generated a numerical scoring or weighting which was determined by Airbus' internal experts from all teams. The exact weightings cannot be revealed due to confidentiality. Additionally, the analysis combined objective measures (such as recurring cost and cash operating costs) with more subjective measures (such as adaptability, assumed technical risks and timescales) based on the results of numerical analysis and expert elicitation. This expert elicitation was undertaken with a group of engineers from Airbus and was recorded using a multimedia capture tool to quantify design foundations. The multimedia tool captured the discussion and rationale behind the expert scores. The purpose of this tool was to reduce information loss and ultimately knowledge loss, whilst providing a means of easily accessing the rationale in a traceable manner. The expert elicitation covered many aspects rather than purely cost and performance. When other less tangible aspects were considered, OEM favored solutions were not necessarily the same as results of normalized analysis.

FIGURE 5. Top scoring configuration for airbus (OEM).

Figure 5 shows a chart of the concept solutions by cost against benefit using a 2015 baseline scenario. The red line in the chart indicates the top twenty configurations (concept solutions) for a fleet with modular technologies that were presented to Airline A (that have a cost-to-benefit score ratio of 1:4). Configurations included the different modular combinations of fuselage, wing type, engine type and design Mach number.

The morphological analysis represented a compilation of Airbus' internal expert's knowledge of real-life constraints and a view of Airbus' preferred solutions. As such, the morphological analysis gives best view of what Airbus could realistically implement. Morphological analysis weightings and rankings were generated by four internal Airbus experts.

This expert elicitation session was recorded and captured and subsequently analyzed for information retrieval purposes. This data resulted in a comprehensive set of solutions that have the potential to meet customer requirements.

E. ACCURACY AND CONSISTENCY CHECKING OF THE HACKATHON OUTPUTS

Checking the consistency and accuracy of the data generated during the hackathon process was a key activity because incorrect data would affect other models and lead to errors in the determination of viable solutions. In order to simulate the hackathon scenario as realistically as possible, real data was used. For example, in the fleet allocation task, the data was compared to real fleet size data provided by Airline A, whilst the economy model results were verified through a sensitivity analysis. A number of models generated data from standard mathematical equations widely used in aircraft design [21].

Data verification was performed differently at each stage, as follows:

1) Overall Aircraft Design (OAD) models were calibrated to demonstrate the behaviors expected based on Airbus' in-house performance software and validated by Airbus' OAD experts. Fuel burn and block time values were sampled and checked against expected values for given distances.

2) Concept generator: a list of feasible combinations was verified against manual permutation of simplified combinatorial sets, to verify that factorial expansion worked as expected. The concept generator was found to produce the correct output concepts in each case tested for these smaller samples.

3) Recurring Cost Model: the Roskam [20] and Raymer [21] methods were used for comparison and visualization to ensure correct behaviors.

4) Fleet Allocation Model: validation was done based on the number of operational hours per day used. Real-life daily operating hours, extracted from data for the target airline were used as operational hours to limit the fleet allocation. With this limit applied, the calculated fleet mix closely matched the real-life fleet (in fact 4 aircraft from actual), also replicating the split between the two aircraft capacity sizes considered to within 10%. A sensitivity study was undertaken to test the impact of varying the operational hours limit that confirmed the expected behaviors. The sensitivity studies also confirmed expected behaviors when varying ticket price and operating costs – i.e. as ticket prices increased and DOC decreased, fleet sizes grew, and airline moved to smaller aircraft to capture all demand, whilst when ticket price decreased, and DOC increased, smaller fleets of larger aircraft were used so that airline could stay in business. Other trends were also consistent with behavioral expectations. OAG [23] and Sabre [24] data were used in the verification and validation of the fleet allocation model following the hackathon along with Airbus' internal performance files.

5) Compatibility of data between models: central templates were developed, and dimensional analysis was completed on units to ensure consistency.

The final output was verified by means of an experienced expert elicitation from Airbus engineers. During the process different modelling and simulation tools were used to produce outputs from each model. Some of the software tools used in the process were MATLAB, Python, Visual Basic scripting in Excel and in parts SimulationX. Use of these tools was very important in terms of ensuring rapid exploration of the data because they were universally understood by the teams. It is possible in future hackathons to introduce more bespoke or specialized tools.

VII. REFLECTIONS, LESSONS LEARNED, CHALLENGES AND REFINEMENTS

A. REFLECTIONS

The aim of this research was to explore the concept and usefulness of a hackathon-style process during the requirements and conceptual design phase of a complex engineered system. The aim of the event from Airbus' perspective was to test the feasibility of undertaking a fleet level technology assessment for a fictitious airline in a time-compressed manner. Airbus was interested in using a real-world case, thus a simulated scenario was used to ensure the processes and methods could be integrated.

This research has successfully demonstrated the value of a systems engineering hackathon as part of an accelerated multi-discipline decision making process (RQ1). It was seen to improve decision-making and consensus of agreement in a simulated large complex project. Lessons learned and future recommendations are presented in this paper to enable the approach to be adopted by others.

The AWI Project hackathon also demonstrated the potential added value of the approach in the quest for effective and efficient system design (RQ2). The systems engineering hackathon was a completely new way of analyzing data using the collective intelligence of industrial and academic experts and allowed Airbus to challenge their thought and design processes in a radically different manner. Full life cycle product data is rapidly becoming the key source of competitive advantage in most industries and a manufacturer needs to understand how the product operates and how it is utilized by operators throughout its lifecycle. Consequently, this information and experience can help guide the design of future products, tailoring them to the needs of specific customers. While airlines may not understand or appreciate the full impact of new technologies, such as modularization in terms of aircraft structure and manufacturing, it was exciting to test 'what if' scenarios as a means to predict what the airline really needed and examine the potential disruption in the usual airliner procurement cycle.

B. LESSONS LEARNED

The major lessons learned can be summarized as following:

1) *Location* - Hackathons are intended to be greatly inspiring and for this purpose the environment in which the process takes place is crucial. It was important to dedicate a specific venue for the activity and to allow the participants to completely concentrate on their tasks during the hackathon event with minimum external distraction. Furthermore, locations with amenities to relax and de-stress were found be beneficial for increasing creativity, for example a quiet room. The AWI hackathon teams were co-located on the Airbus site and this was important because it ensured all key players were available, and those that were required to undertake the consistency checks throughout the process were on hand. This brought focus and enabled collaboration more easily. It also allowed people to work in the collaborative spirit of the event. Furthermore, the physical space and resources were important in enabling successful collaboration. The ability to collectively write on large whiteboards, have space to work in groups on laptops and break-out areas for discussions - including provisions for continuous refreshments - were all important factors.

2) *Keeping participants on-track* - Hackathons are typically very exhausting [25] and organizers should make arrangements to support participants in staying focused, active and motivated. For example, talks or presentations were kept to limited time periods because they could disrupt the flow of progress. In general, it was found to be extremely helpful to have a well-planned and non-complex schedule to allow the project to develop gradually and progressively. The presentation on progress at the end of each day (and overall presentation at the end of the event) reinforced the hackathon goal and provided an opportunity for a wider group of people within the company to see the results of the work.

3) *Timing* - The level and composition of attendance was extremely important; therefore, a time was selected when participants were not expected to be attending other events. This posed difficulties in organization but it was felt that if real value was to be extracted from the event then everyone must be committed for the duration. Intensive events like the AWI hackathon required a small amount of time to gain momentum and setting aside five days for the event was found to be an ideal duration [26].

4) *Collaboration* - Meeting and working closely with other partners involved in the project was beneficial for all the attendees and was found to be a very productive way to achieve results. In addition, all participants had a better collective understanding of the problems they were trying to solve upon completion of the event. There was also a considerable amount of knowledge transfer and technical information exchange between different team members. Furthermore, it was a great opportunity to work through complex technical problems with partners from various backgrounds and technical skills,

which increased the likelihood of being able to find useful technical solutions and significantly accelerated progress by developing trial and error approaches for such solutions.

5) *Research into practice* - Another positive outcome of the event were the discussions about how to obtain valid results. One of the organizers commented, ''One of the most useful outcomes of the event was putting research in practice which was previously abstract and difficult to interpret and also getting to a stage to do a dry run of integrating work packages.''

6) *Flexibility* - There was benefit in striking a balance between prescribing rigid goals and methods against having fairly open-ended and loosely defined tasks. This was a difficult balance to achieve during the hackathon as it requires high co-operation. However, the vision was clearly set with some recommendations and the methodology was agile enough to provide a suitable degree of flexibility. This approach helped align people to a goal but allowed room for new ideas and innovative thinking to emerge.

7) *Team size* - The team size was found to be ideally between 5 and 6 participants per team. If the team was too large it was found that sub-teams would naturally form and there was a danger of the sub-teams losing focus.

8) *Co-operation* - The AWI hackathon was co-operative not competitive. The potential drawback with co-operative teams is the risk of losing a motivating competitive edge. However, by organizing the teams to require a close reliance and interdependence on other teams and individuals, meant that participants were driven to progress and intrinsically felt that their contribution was important.i

9) *Peer review* - At the end of each hackathon day a plenary session was run whereby people external to the hackathon could participate (remotely or in person) in a review session to discuss progress and next steps. The external participants were permitted to ask questions or be asked about specific points of interest.

10) *Duration* – It was found that a duration of 5 days was close to the maximum limit of effective intensive working. It was long enough to tackle a more ambitious challenge than those usually tackled during a 24-hour or weekend hackathon. It was felt perhaps difficult to schedule and motivate a large group of people for longer than a week, especially when they have other work responsibilities.

11) *Realism* – Including the stakeholder role of 'customer' made the hackathon a more realistic situation and helped participants to become and remain engaged.

12) *Researcher involvement* - The anonymity and adaption of Airbus data was a useful means of enabling partnering university academic researchers to get closely involved in the task, which they otherwise would not have been able to due to confidentiality issues.

C. CHALLENGES AND REFINEMENTS TO FUTURE HACKATHONS

Synthesizing the results of the work at the end was a challenge as there was a great deal of information in various formats residing with different individuals. Gathering that information, sense-making and presenting that back was difficult, especially in a short space of time during the event. Planning how this is to be addressed before the event and using supporting tools to help with this is recommended.

Based on the participants' feedback some suggestions were made to refine future hackathon events.

1) A short summary at the end of each day from each team would be useful in bringing all partners up to speed on overall progress.

2) Establish an agreed method, format and tools for data sharing to advance progress more quickly and avoid unnecessary additional work.

3) An engineering team member said, ''It would be beneficial to nominate a team member to work directly with other teams for periods of the time during the event in order to be able to link groups.''

4) The hackathon requires a good facilitator who has a good grasp of the problem being addressed.

5) The architecture team leader said, ''the event could be improved by providing examples beforehand of coding expectations, for example what level of testing and proof-reading is expected''.

6) It is critical to allocate enough time in task planning to account for quality control checks. Moreover, setting up an easy to use assumptions log (e.g. flip-chart, etc.) to quickly record assumptions if participants are not able to directly annotate models.

7) Encourage greater self-organization amongst teams and make sure that exchanges between teams are not just limited to a few focal points.

8) Consider the implementation of version control guidelines for models to ensure robust quality control.

9) If all data could be captured and modeled within an interactive modelling or simulation tool (or set of coupled tools) then there is potential for the design space to be explored interactively in near real-time and 'what if' scenarios could be explored between the stakeholders.

VIII. CONCLUSION

The design of complex engineered products and large scale manufactured systems is a complicated and lengthy process that traditionally takes months or even years. The design complexities are such that no single person or discipline can make the necessary design decisions that ultimately determine the final 'shape, form and function' of the product. Instead, the many decisions taken by a multi-disciplinary team must be considered. It is necessary to consult external and internal stakeholders too, including the end customer, who might radically impact upon different stages of the process and outcomes. Thereby making the time from conception to new

product launch incredibly drawn-out and presents a challenge in keeping ahead of competitor products.

This paper describes a novel systems engineering hackathon event organized by Airbus. The research aimed to explore the approach as an accelerated multi-discipline process to improve decision-making and consensus of agreement in a large complex engineered project - in this case the design of a hypothetical future aircraft. The research examined the interactions and effects of the various stakeholders' involvement and their roles. All stakeholders were extremely satisfied (based on an after-event review questionnaire) at how much 'ground' had been covered in less than one week – and which would previously have taken many weeks and months to go through top-level options. The level of communication across the disciplinary boundaries was found to be a very powerful mechanism for explaining and discussing the different goals and constraints that different stakeholders needed to optimize against.

The hackathon process described in this paper would not be used to design a complex product from beginning to end but was found to be a powerful technique to scope out, discuss and define key decisions between all stakeholders during the concept design phase. It has proved to be a very successful method to rapidly achieve a shared level of understanding between teams. Consequently, the hackathon process has significant potential to be used during the very early phases of product design when immediate customer interactions are required to rapidly articulate and understand their needs and therefore help to produce better and more feasible customer focused solutions. Lessons learned and recommendations for future systems engineering hackathons are presented.

At the end of the hackathon event the entire process and outcomes were presented to Airbus' internal management, experts and customers, resulting in strong buy-in to the approach and future hackathon events are being planned within Airbus. It is a process that could also be usefully adopted in other manufacturing contexts.

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