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The Application of an Agent Based Impact Analysis to a Complex Air Traffic Management System

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It is both costly and time consuming to predict the behavior of complex systems due to their data intensity. They also tend to be dynamic which means they may not lend themselves to a quantitative behavioral analysis. An impact analysis is presented as being a novel qualitative approach with the aim of determining, qualitatively, how a system element deviates from a pre-defined “normal” operational mode due to a change in the operation of another element existing within the same architecture, or due to an interaction with an external environmental condition. Performing such an analysis determines elements in the system that would be affected by the change and aids in system development through identification of relationships and interdependencies prior to modifications. Air Traffic Management (ATM) systems are examples which would benefit from such analyses. This paper presents two impact analyses; one of which encapsulates a complex real world scenario involving the Icelandic Volcanic Eruption in April 2010, the other a series of localized scenarios focused on London Heathrow. The potential and capability of the model and approach to understand more about how the ATM system operates, and how its behavior evolves through scenarios, have been emphasized through these analyses. The agent based impact analysis is shown to identify the elemental relationships and interdependencies in a simple qualitative manner whilst not being data intensive.

I. Introduction

System-of systems are complex structures which incorporate numerous self-contained, interconnected systems, each of which can be further broken down into components which interact with one another heterogeneously. Furthermore these systems tend to be evolutionary and exhibit emergent behavior, resulting in them often being difficult to analyze. This can lead to uncertainty surrounding performance characteristics and the predictability of system behavior. These systems can occur naturally, within the environment¹ or be man-made².

Current methods for predicting the behavior of such structures are both time consuming and costly, due to their data intensity, and in some instances they can be highly dynamic in nature and therefore do not lend themselves easily to a quantitative behavioral analysis. However, despite the recognized difficulties in their realization, the creation, development and modification of complex systems and system-of-systems are becoming increasingly commonplace. The key to understanding such system behavior arises from both the identification of interdependencies and understanding the consequences to the overall system state due to the data transfers across these interdependencies. This information is usually acquired through a secondary analysis of the behavioural and physical models where the aim is to identify when changes in one parameter or element affects and/or changes the behaviour of another. This can present numerous challenges as in real world systems even obtaining the base behavioural models is difficult due to the ever-increasing size and complexity.

An Air Traffic Management (ATM) system is an example of a man-made system-of-systems which displays these typical characteristics. The European ATM system operated and controlled 9.7 million flights across the 38 member states in 2007³, with peaks of 32000 flights per day⁴. This figure was predicted to rise at a rate of 2.3-3.5% per year, with 16.5-22.1 million flights forecast for annually in 2030. The 38 member states comprise 1740 air

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traffic control sectors containing 560 airports and 75 en-route centers⁴. The 9.7 million flights incorporated 250 aircraft operators⁵, organizing and managing to ensure a safe and efficient service. This complexity is also present at the lower levels of the European ATM hierarchy. At the UK national level the National Air Traffic Service (NATS) was responsible for handling 2.2 million flights and 200 million passengers in 2009⁵. At the airport level, Belfast International offers flights to 41 different destinations through 26 airlines. The complexity of the ATM system is further increased due to the differing rules and regulations across the member states.

These ATM systems are currently in the process of being modified to increase their efficiency, cost-effectiveness and safety. The capacity of these systems must also be increased due to the constantly rising demand for air travel. SESAR⁶ and NextGen⁷ are examples of such initiatives, with SESAR concerned in the application of a 'single sky'⁸ implementing consistent rules and regulations across the member states and direct to destination flight routes. This makes an ATM system an ideal candidate for the demonstration of impact analysis techniques, such as is presented in the current work

The complexity of the ATM system hierarchical structure is demonstrated by the large number of self-contained systems which exist within it, such as airports, sectors and control centers. These systems can then be further divided into smaller complex systems such as aircraft and airport control. The number of elements and sub-systems within the structure are subject to change due to the dynamic nature of the system. Sector size and capacity can change depending on the current operations whilst the number of aircraft alters depending on the system requirements and demand.

The elemental interactions existing in the ATM system are diverse and can range from electronic data transfers to human-human interaction. In many instances system elements will be participating in multiple methods of communication, which are simultaneous and between different levels of the operational system hierarchy. In light of the number of operations undertaken within the ATM system at any instance in time, this demonstrates a high level of complexity, which makes any analysis approach challenging.

Furthermore the system is susceptible to both human factors and environmental constraints, which are outside the direct control of the system itself. These factors introduce a range of potential sources of error within the architecture, and remain a challenge for their safe implementation.

Preliminary tests of current ATM behavioural analysis techniques, such as process modeling and influence diagrams, demonstrated the approaches to be costly, data intensive and time consuming. A large number of studies consider the definition of impact, and there has been wide variations dependent on the context to which it is being considered including performance, sensitivity and design analysis^{9,10,11}. These tend to be highly detailed, large scale and quantitative analysis procedures and are therefore data intensive and computationally expensive.

Notably, the identification of system impacts exhibits two difficulties:

1. Behavioural models are focused on precise definitions of parameters and physical or observed behavior. In large systems these are therefore limited by computational power and ability to provide detailed validation of all aspects of system behaviors.
2. Large dynamic (live) systems are inherently multidisciplinary in nature, comprised of diverse data sets, which makes the development of coherent/common definitions of the existing data relationships extremely difficult.

Davies et al¹² addressed these challenges by developing a generic definition of impact which cut across disciplines and developed a flexible model which carries only impact data. The aim of the analysis was to provide information such as regions of interest or bottlenecks where more detailed physical or behavioral models may be needed.

The agent based model developed demonstrated that it was possible to understand more about how the ATM operates, and how its behaviour evolves through a number of applied scenarios. The potential for further analysis of larger scale system scenarios, more representative of the fully functional ATM system was identified. At this stage only logical verification had been carried out, though development of the technique and modeling approach resulted in a fuller validation being achieved through the analysis of a localized UK ATM system model¹³.

This work therefore continues research into the application of an agent based impact analysis to a more complex ATM system model. Prior to a discussion of the analyses, it is necessary to recall the definition of impact and the modeling approach.

II. Impact

Impact is defined as the measure of how a system element deviates from a pre-defined “normal” operational mode due to a change in the operation of another element existing within the same architecture, or due to an interaction with an external environmental condition. This qualitatively determines the elements in the system that would be affected by a modification. It can also aid in system development by identifying relationships and interdependencies prior to implementation.

The precise definition of an effect is a function of both the specific application under study, and the modeling or simulation technique in use (for instance, linked to measureable quantities, heuristic measures or simple logical indicators). The impact is then determined by a user-specific combination of the effects which are realized within a particular system element. Although impact is a qualitative approach, it is converted to a user-defined quantitative measure to assist in the computational process. An example of this scale is shown in Figure 1.

The function of an impact analysis is to therefore:

- *Identify* element relationships and interdependencies
- *Analyze* the impact of one element on any or all of the elements within the system architecture.

An impact analysis is potentially a powerful approach in analyzing the influence of one element on the system architecture, whilst identifying relationships and interdependencies between all constituent elements.

The impact on any element is characterized by the effect(s) that is realized elsewhere in the system architecture. An effect is defined as a mathematical indicator of the state of an individual aspect of an element, which must fulfill the following criteria:

- Must be dimensionless
- Must have a value ranging between 0 (nominal operation) and 1 (non-functional)
- Must be defined in terms of input values
- Must have a defined “normal” operational state (zero value)
- Must be related to at least one input/external factor
- Must represent one or more of:
 - Output value
 - Internal state
 - Internal operation

The precise definition of an effect is a function of both the specific application under study, and the modeling or simulation technique in use (for instance, linked to measureable quantities, heuristic measures or simple logical indicators). The impact is then determined by a user-specific combination of the effects which are realized within a particular system element. Although impact is a qualitative approach, it is converted to a user-defined quantitative measure to assist in the computational process. An example of this scale is shown in Figure 1.

Figure 1. Impact qualitative scale

The quantitative measure of impact used for the computational process is calculated using:

$$I = \min \left(\frac{\sum_{i=1}^n \alpha_i I_i}{n}, 1 \right) \quad (1)$$

where,

I_i is the impact on system element i

α_i is the importance factor of element i

n is the number of elements within the sub-system

There are two classes of impact which occur within a system. The first, Hierarchical, refers to impact calculated within the system hierarchy, whilst stakeholder refers to the impact is calculated based on the relevance of elements to a given stakeholder.

A. Hierarchical Impact

This is reference to impact which is calculated at each level of the hierarchical system structure. Therefore the hierarchical impact can be further decomposed into a number of subsets; System Impact, Sub-system₁ through to Sub-system_n impact and elemental impact. Hierarchical impact must be calculated using elements or sub-systems on the same level of the system hierarchy. Analysis of hierarchical impacts identified that impact on the lowest level elements can be absorbed within the system though this is dependent on the number of elements within the sub-system at any point in time.

It is worth noting the influence of mobile elements in a system on the calculation of hierarchical impact, and the importance of a correctly defined system hierarchy. Impact on the elemental level may be large, even to the point of rendering the element inoperable, though this may be only a fraction of the impact on the overall system. Furthermore impact transferred by mobile elements may be absorbed in larger sub-systems.

However, hierarchical impact is not always of interest to all of the stakeholders within a system, and therefore a second measure, stakeholder impact, is required.

B. Stakeholder Impact

Whilst hierarchical impact is concerned with the operational system hierarchy, stakeholder impact considers the stakeholders in the system though it can only be calculated for elements/sub-systems on the same level of the hierarchy.

There are many stakeholders present in, or related to, a system. These stakeholders are generally not interested in all aspects of the system; rather they are concerned with those aspects which affect them. For instance, an airline is generally only interested if something affects their flights or aircraft. The interest in the other aspects of the system is a secondary consequence when trying to discover why their flights/aircraft are affected. This impact is especially useful when applied to larger complex systems where airlines would be interested in the impact on all aircraft or aircraft on a particular route.

Additionally, there may be stakeholders who are only interested in airports or impacts on certain airspace, for instance government bodies. Therefore the stakeholder impact is that which acts on a group of associated elements whose relationship may not be demonstrated through the system hierarchy.

III. Modeling Approach

In order to develop a representative system model on which to demonstrate the impact metrics defined above, the example ATM system models were developed using an agent based modeling approach, using an AOS Java integrated development platform called JACK¹⁴. Agents were chosen since they can naturally sit simply looking for change. The resulting application is therefore focused only on the data linkages between system elements and any changes in these that may occur.

There are 5 main class level constructs¹⁵:

- *Agents* determine the behavior through a combination of the associated capabilities, events and plans.
- *Capabilities* are composed of plans, events and beliefsets, which are then applied to an agent.
- *Events* describe an event an agent must respond to. When an event occurs this generates a goal for the agent which selects a plan to achieve it.
- *Plans* contain instructions on how to responds to an event and achieve a particular goal.
- *Beliefsets* represent agent beliefs and are created using a generic relational model.

The impact analysis is being applied through system operational simulations and therefore needs to model all elements of the system. Within the model, the system elements may have the ability to make decisions based on their current information and agent based modeling incorporates this concept with the agent construct being able to choose which plan to follow to achieve its' goals based on the information it has at that point in time.

Furthermore, this modeling approach has the capability of inter-agent communications allowing agents to share information to achieve a goal, mirroring real world systems where two or more system elements must work together.

IV. UK and Ireland ATM System Model

The previous sections have discussed the analysis, the approach and the development environment. This section will review how these have been incorporated to provide a tool to determine impact on the UK and Ireland ATM system model.

Davies et al have developed the agent-based impact analysis through both a simplified model¹², consisting of a test system with 2 airports and 5 aircraft, and a localized UK system model¹³, incorporating 21 of the UK airports and a user defined number of flights. Application of simulations to the latter model concluded that improvements were required, including:

- providing the ability to apply reduced runway operations (only take-off or land) as opposed to only closing the runway
- providing the ability to model diverted aircraft
- incorporating flights which originate or terminate externally to the modeled UK ATM system
- modeling the correct number of runways at each of the modeled airports

These have been developed and incorporated into the current model which also comprises more efficient programming, further utilization of timer and agent constructs and the introduction of a Central Flow Management Unit (CFMU) to improve the overall model efficiency. In addition to these it was noted that to improve the fidelity of an ATM system model it would be necessary to represent flights which have multiple flight numbers due to connecting flights (codesharing).

This model introduces the ability for 'real-time' impact management, allowing the user to alter impact boundaries, importance factors and computational impact values. Airport and enroute control are now featured in the model and can also be impacted. Furthermore, current qualitative levels of sub-system and system impacts are visually represented on the user interface, all of which utilize the current user defined impact boundaries.

The elements modeled in this system include the 21 airports, 22 sectors (21 airports and 1 enroute) and the user-defined aircraft. The aircraft can be internal flights or flights departing or arriving at the system airports. The elements are modeled as such;

- I. The airports are modeled as objects with characteristics which can be manipulated. The runways at each airport can be either available or unavailable. The weather at each airport has 4 potential states; safe, safe for landing only, safe for take-off only and unsafe. Finally the number of aircraft that can be controlled comfortably (without impact) can be altered. It must be also noted here that Manchester (MAN), London Heathrow (LHR) and Dublin (DUB) are modeled as airports with 2 runways which are independent of one another.
- II. The sectors are modeled by applying a location to each of the aircraft. The aircraft can be at any of the airport sectors, the enroute sector, external or inactive.
- III. Airport and enroute control are modeled as objects with the ability to handle a given number of aircraft comfortably at each location. If the number of aircraft increases beyond this, it will result in impact on the element. These values are changed via the airport or options interface.
- IV. The Central Flow Management Unit is represented by a single agent construct. This agent is responsible for creating the aircraft agents at the appropriate system run time. In previous models all aircraft constructs were present from the start of the simulation which was deemed inefficient.
- V. The aircraft are modeled as agents. It is assumed each flight number, excluding codesharers, corresponds to an individual aircraft. Every aircraft corresponds to its own agent with independent characteristics such as flight number, airline, destination, departure airport, etc. The aircraft all have a "flying" capability which corresponds to a number of "flight stage" plans including; start, take-off, enroute, land and end. With the inclusion of diversions, externally originated and terminated flights further plans have been implemented including divert, enter UK airspace and exit UK airspace.

Furthermore a number of other agent constructs are required known as ‘Impactors’. These agents are responsible for monitoring the aircraft and determining the various impacts associated with the system. As mentioned earlier there are two types of impact and there are 3 agent constructs responsible for calculating these.

- I. The ‘Elemental Impactor’ is responsible for monitoring all *active* aircraft, determining and outputting their associated elemental impacts. This agent will also determine and output the impact of each airport and enroute control.
- II. The ‘Sub-system Impactor’ is another construct responsible for calculating hierarchical impact. This agent analyses each *active* aircraft and applies the impact to the aircrafts current location to allow a sub-system impact to be calculated. The sub-system impact also includes the impact from the associated control. This impact is then visually represented on the user interface.
- III. The ‘Stakeholder Impactor’ calculates the airline stakeholder impact. This agent analyses each aircraft and applies the impact to the appropriate airline. The stakeholder impact for all control stations is also calculated and output.

There are 2 final agent constructs present in the system model with the purpose of organizing and implementing scenarios. The model not only allows for ‘real-time’ scenarios but is capable of modeling larger, more complex scenarios which can be defined through a scenario input file.

- I. The ‘Scenario Builder’ generates ‘Scenario’ agents when they are required during the simulation based on the information acquired from the scenario file.
- II. The ‘Scenario’ agent identifies the type of scenario required and implements as necessary.

Figure 2 depicts the system protocol, showing the system operations from start to finish.

V. Scenarios

This section will outline the scenario simulations which have been applied to this system model. There are two analyses to be performed using the impact model. The first analysis introduces a scenario utilizing real world data from April 2010 during the volcanic ash cloud disruption to the European ATM system, whilst the second applies a number of comparable localized scenarios to London Heathrow and examines how the system responds.

A. Volcanic Disruption

In the previous study by Davies et al a scenario emulating the extreme weather conditions experienced during December 2009 in the UK was simulated using the earlier model¹³. This allowed the model to be tested against a complex scenario which put the ‘real-world’ system under stress. In April 2010 the UK ATM system was again disrupted by an unforeseen natural phenomenon with the eruption of the Eyjafjallajökull volcano in Iceland. This sent the UK and European ATM systems into chaos resulting in mass cancellations and airport closures. After a number of days some flights began operating again, though the system still maintained a large number of cancellations and delays.

Therefore it was decided to simulate a scenario from one of these days through the impact analysis tool. Data was collected¹⁶ for all flights operating at the 21 airports for the 21st April 2010. On this date there were 9319 scheduled flights operating, originating or terminating within in the UK system, of which 3804 flights were cancelled. It must be noted that these figures include codesharing flights. The data collected includes the flight numbers, airline, scheduled times of arrival and departure (STA and STD), and the airports involved. This allows the system to develop a flight plan for each of the aircraft with the duration of the flight being calculated from the difference between the STD and STA. Data was also collected with regards to the actual time of arrival to allow for comparison of the results.

Figure 2. UK and Ireland ATM system protocol

B. London Heathrow closure

The next analysis incorporates 4 comparable scenarios focusing on London's Heathrow Airport (LHR) and uses the flight data collected for the Volcanic Disruption analysis and will simulate from 06:00 onward. The 4 scenarios will be as follows:

- Short closure
A 1 hour closure of LHR will be implemented from 09:00.
- Short delay with diversion.
A 1 hour closure of LHR will be implemented from 09:00. All incoming flights will be diverted to London Gatwick Airport (LGW). It is assumed LGW has the capacity to cope with the excess aircraft.
- Full day closure.
LHR will be closed for the duration of the simulation with all flights designated to depart or arrive at the airport being cancelled.
- Full day closure with diversion.
LHR will be closed for the duration of the simulation with all outbound flights cancelled. All incoming flights will be diverted to LGW. It is assumed LGW has the capacity to manage the excess aircraft.

The concept of a full day closure at an airport such as LHR arises from the recent threats of strike action from British Airport's Authority (BAA) staff¹⁷. BAA currently owns and operates six airports within the UK including LHR, London Stansted (STN), Glasgow (GLA), Edinburgh (EDI), Aberdeen (ABZ) and Southampton (SOU). During these threats there was a discussion on whether flights would be cancelled, diverted or a combination. Therefore it was decided that an impact analysis would be performed on LHR incorporating the first 2 options. The other scenarios allow it to be compared with a shortened version.

Any aircraft that are cancelled will automatically be declared inoperable due to their cancelled status, whilst diverted flights will experience a high impact due to the change in location of the flight which would result in both aircraft and passengers finishing in the wrong location.

VI. Results

The system model and protocol have been discussed and the analyses have been outlined. The data set was input into the system and the impact analyses performed for each of the scenarios. The results of these will be presented in this section.

A. Volcanic Disruption

The maximum computational elemental impact for each of the flights has been extracted from the simulation results. These results have been compared graphically to the 'real-world' data in Figure 3. The graph only depicts the comparison of a small portion of the flights. This is due to:

- Only localized flights can be compared as flights originating or terminating externally are not fully modeled
- Cancelled flights are pre-programmed and are therefore not comparable
- Codesharing flights are represented by the original flight number.
- Some of the data collected is incomplete or inaccurate.

Figure 3 depicts the flights in order of increasing delays as taken from the real system and is used simply as a means of comparison between the real world flight delays and the simulated impact. The graph demonstrates a good correlation between the simulated results and the real world data. There are a few anomalies highlighted by the graph which occur firstly around aircraft number 290, where the impact is over predicted, and again at flight number 300, where the impact has been under predicted. These relationships will be discussed in the next section of this paper.

Figure 3. Comparison between real world delays and computation impact from model simulation

The sub-system impacts on the UK ATM system for the volcanic disruption are shown in Figure 4. There a number of key points indicated by this graph:

- Three of the London based airports are the first airports to be impacted; LHR, LGW and STN. This occurs between 5 minutes and 40 minutes into the simulation with the impact arising from a number of night flight cancellations including; 5 at LHR, 3 at LGW and 1 at STN.
- The other airports are not impacted until between 360 and 405 minutes into the simulation. The scenario begins at 00:00 on the 21st April and therefore these airports are impacted between 06:00 and 06:45. Many of these airports do not operate outbound night flights, especially in off-peak traffic throughput. This time therefore corresponds to the first early morning flights, which due to the ash cloud, are beginning to be cancelled.
- The impact at London Luton (LTN) never exceeds the medium level, making it the least impacted airport. This is due to LTN having the least number of cancelled flights, with only 2 during the simulation; Flybe flights BE163 to Jersey and BE164 to the Isle of Man.
- For all airports, the impact at the conclusion of the scenario remains medium or high. This arises from the flights which have been cancelled as they never exit the system and therefore their impact is retained within the system.

It is difficult to identify other points of interest due to the mass fluctuations illustrated in Figure 4 from 360 minutes onwards which make it difficult to decipher the impacts of each of the airports. Therefore viewing and understanding the impacts from a large number of sub-system impacts for a complex scenario in one graph is not possible.

Due to this a sample of the sub-system impacts, BFS and LHR, are shown in Figure 5 where it is simpler to identify points of interest, and understand what is happening within these airports.

The sub-system results for BFS and LHR, in Figure 5, have been divided into 3 sections:

1. In section 1 the impact in BFS is nominal as the only scheduled flight prior to 06:15 is the outbound Thomas Cook flight to Manchester scheduled for 03:40 which departs on time. Conversely, LHR experiences medium impact almost immediately corresponding to 2 cancelled outbound flights. The impact rises further as another 3 flights are cancelled. The impact on LHR remains high until 55 minutes into the simulation (00:55) when it is reduced to a medium level due to the Transaero Airlines flight to Moscow entering the system and taking-off on time. Upon taking-off the impact on LHR is reestablished as high. This section finishes approximately 130 minutes into the simulation (02:10) and LHR has 8 cancelled flights at the airport.
2. The impact on LHR is consistently high throughout section 2. At the conclusion of the section, 710 minutes into the simulation (11:50), there are 859 cancelled flights within the airport (including codesharers) and of the 141 that have departed there have been large delays. BFS is still operating nominally in section 2 up until 376 minutes into the simulation (06:16) when it experiences low impact. This arises from the flight data reporting 2 flights due to depart at the same time, and hence one experiences a very short delay. Once it departs BFS the impact is removed, though a short time later the BFS is medium impacted. This corresponds to Easyjet flight 732 to London Gatwick being cancelled. The impact then increases to high at 435 minutes (07:15) when a further flight is cancelled. This is the Aer Lingus flight to London Heathrow which also has a British Airways codeshare. The fluctuations which follow arise due the next 18 flights which are due to depart up to the end of section 2. Of these 18 flights, 8 are cancelled, whilst the remainder departs on time. The departing flights are responsible for the short periodical troughs where impact becomes medium. At the end of section 2 there are 12 cancelled flights responsible for the high level of impact on BFS.
3. In section 3 the impact on both airports is high this is due to the high proportion of cancelled flights. The flights which do take-off are no longer capable of absorbing the impact from these cancelled flights corresponding to the increasing ratio of cancelled flights to active operational flights

This demonstrates clearly that with only 2 sub-systems represented in Figure 5 it is much easier to gain an understanding of the system operations when compared with Figure 4.

The system impact corresponding to the volcanic disruption scenario is presented graphically in Figure 6. This graph illustrates the impact rising from nominal to high through the duration of the scenario. This increase occurs in three steps; nominal to low, low to medium and medium to high which are clearly highlighted by the graph. To aid in the understanding of these increases Figure 3 also incorporates 3 impact maps of the UK ATM system at the appropriate points in time. It must be noted that the impact map does not distinguish between nominal or low and represents them both as green zones. This is the same for high and inoperable which are both red zones. Furthermore the maps also give an approximation to the location of the ash cloud through the red boundary line.

The step changes arise from the following:

- Nominal to low
This increase occurs 4 minutes into the simulation (00:04) and the corresponding impact map clearly indicates this is due to LHR being highly impacted.
- Low to Medium
The impact map for this increase demonstrates that at this point in the simulation 5 of the 21 airports are now highly impacted and 4 are medium. It is this distribution that pushes the system impact to medium.
- Medium to High
The final increase is again explained clearly through the impact map, where now only LTN remains in the green zone. BFS and EXT experience medium impact, whilst the other airports are now highly impacted. With such a large proportion of the sub-systems highly impacted, the system itself experiences the high level also.

Following the medium to high increase the impact does fluctuate a number of times over a very small period due to changes in impact at IOM, LGW, PIK and SOU sub-systems.

The impact maps show that the location of the ash cloud does not pre-determine the impact on airports within it. In the first map this is due the majority of airports not operating flights until 06:00 so they cannot be impacted and therefore it is not possible to see any impact of being in the ash cloud zone. The differences in the other maps arise from the varying flight routes at each airport. Many of the flights to and from eastern or northern airports external to

the system were allowed to function which therefore reduces the impact on some of the system airports. Therefore airports in the ash zone could have reduced impact levels. Conversely those system airports operating routes to southern and western, external locations will find many flights cancelled, resulting in airports outside of the ash zone being further impacted.

Figure 6. System impact results for the volcanic ash scenario and corresponding, mapped sub-system impacts

B. London Heathrow Closure

The results for both the sub-system and system impact have been determined for the four scenarios. The results of the sub-system impact, for each of the scenarios, are presented in Figures 7 to 10. These graphs demonstrate the impact for the duration of the simulations for 10 of the 21 airports. The airports not represented did not experience any unexpected impact in the scenarios. They only demonstrated small fluctuations from nominal to low impact that have been caused by small delays in the system which can be referred to as *impact noise*. Removing this noise from the graphs would make it easier to identify points of interest.

Figure 7. Graph showing the sub-system impact for the short closure scenario

Figure 7 depicts the sub-system impact for the short closure scenario. The short closure is easily identified by the inoperable impact experienced by LHR which has a duration of 60 minutes. Apart from this peak there is no impact above low experienced by any airport. At all other times the airport impacts fluctuate from nominal to low demonstrating normal impact noise that would be expected in such a large system, even without the closure.

Conversely, the results for the short closure with diversion scenario (Figure 8) show a number of peaks within the system run time. As with the previous scenario LHR has an inoperable impact level corresponding with the closure being implemented, but during this time a number of airports experience medium impact levels. The airports affected are NCL, GLA, ABZ and DUB, with MAN being hit as the closure ends. Prior to LHR closing, the results show the airports to be experiencing impact noise. This is repeated after MAN returns normal.

Figure 8. Graph showing sub-system impact for the short closure with diversion scenario

Figure 9. Graph showing the sub-system impact results for the full day closure scenario

Figure 10. Graph showing the sub-system impact results for the full day closure and diversion scenario

The results for the full day closure of LHR are shown in Figure 9. LHR has an inoperable level of impact for the duration of the scenario corresponding to the closure of the airport. LGW experiences impact noise throughout the simulation whilst the remaining airports experience medium to high levels of impact. GLA airport is the first to be hit due to the closure with a high level of impact and from this point on fluctuates from medium to high before maintaining a high level of impact for the remaining time. DUB and ABZ both change from nominal to medium and medium to low shortly after GLA's rise. The impact level at both airports then becomes high and then follows GLA by fluctuating between medium and high for a short period before moving to high permanently. BFS and NCL move to high levels of impact around the same time as GLA, but in their case they fluctuate for most of the simulation between medium and high levels of impact. NCL remains high from approximately the 700th time step, whilst BFS does so at the 800th minute. MAN is the last airport to move to medium and high levels of impact but follows the other airports with some fluctuating between the two before settling on high.

Figure 10 shows the sub-system impact for the final scenario. The impact on LHR, as with the previous scenario, remains inoperable throughout. Unlike the previous scenario none of the other airports experience an impact level above medium. The other airports, with the exception of LGW, fluctuate rapidly between nominal, low and medium for the duration though all return to nominal prior the end of the simulation. LGW, on the other hand, fluctuates only between nominal and low impact throughout.

It is now necessary to present another set of results. Two of these scenarios have incorporated diversions implemented at LHR, which results in incoming aircraft being redirected to and landing at LGW. The results presented for each scenario depicted the impact at LGW fluctuating between nominal and low throughout. Unlike the other airports the impact never exceeded the low level. The impact results that were presented in Figures 7-10 show that LGW is relatively unaffected by any of the scenarios, even with increased inbound flights diverted from LHR. To demonstrate that the scenarios did indeed impact LGW differently, Figure 11 presents the computational impact values for each of the scenarios.

Figure 11 has been scaled to highlight the fluctuations. From these computational results it is possible to see the short closure scenario impacts LGW the least. The results for each scenario shows the impact fluctuating throughout the periods with the closure and divert impacting the airport the most, followed by the short closure with diversion and the full day closure.

Figure 11. Comparison between the computational values for London Gatwick for the 4 scenarios

Figure 10. Comparison between the four closure scenarios

The system impact results for each of the scenarios are illustrated in Figure 12. The results show clearly that the closure scenario has the biggest impact on the system, with the impact rising from nominal to low as the simulation begins. Approximately 60 minutes into the simulation, the impact becomes medium. This returns instantaneously to low for a short period before rising to medium for the remainder of the simulation. The other scenarios indicate the system impact to be nominal for a short while before moving to the low level. The impact for the full day closure and divert scenarios remains low whilst the other 2 scenarios experience a number of fluctuations between low and nominal toward the end before returning to nominal impact.

The results for both of the analyses have now been presented and compared graphically and will be discussed further in the subsequent section.

VII. Discussion

This section will discuss the results that have been presented for both impact analyses beginning with the volcanic disruption.

A. Volcanic disruption

The volcanic disruption analysis incorporated a complex real world scenario with flight cancellations and reduced airport operations. The results extracted from the simulation were presented for a comparison with the real world scenario and a comparison between the simulated sub-system impacts.

Figure 3 compared the two sets of data, though of only a small proportion of the flights are comparable due to the reasons provided. The results demonstrated a good correlation between the real world data and the impact from the simulation. The comparison highlighted a few anomalies, where impact was either over or under predicted. These arise due to:

- Over predicted
 - The flight data collected contains a number of approximated landing times which may indicate inaccuracies from the real world scenario.
 - A simulated flight has been due to take-off prior to reduced airport operations and has been delayed slightly meaning it can no longer take-off due to the implemented scenario. This accounts for the points which show the greatest difference including the almost inoperable flight at approximately 376 minutes.
 - The system model operates a first come, first serve protocol for taking off and therefore it is possible this induced a small impact change.
- Under predicted
 - During the ash cloud disruption in the real system, a number of flights were delayed whilst other flights at the same airport took off. These delays may therefore have been caused by the airline or other unforeseen circumstances.
 - The system model does not have a human-in-the-loop characteristic, unlike the real system.

The volcanic ash cloud imposed a complex scenario on the complex, real UK ATM system. Analyzing such an event using this model can only incorporate scenarios that can be deduced from the data and therefore makes it difficult to replicate.

Figure 4 depicted the results for all the system impacts and a number of points of interest were highlighted. The graph also emphasized the increased probability of an airport sub-system being impacted when running flights through the night due to the increase in traffic throughput. This was demonstrated by LHR, LGW and STN being greater impacted by the ash cloud than those airports operating few or no flights between 00:00 and 06:00.

The large fluctuations shown in Figure 4 arise from the dynamic nature of the sub-systems, as during the simulation the number of elements present in each sector is constantly changing. The scenario incorporates a large number of cancelled aircraft that are currently impacting their origin airports. Therefore, during periods of fewer flights within the airport, the impact from the cancelled flights is more prominent.

Of the 21 airports, 20 have high impact when the simulation terminates. This high impact is also a result of the cancelled flights within the system, as they never leave the system. LTN is the only airport to end the scenario with less than high impact. The medium impact experienced by LTN is caused by cancelled flights but much fewer than the other airports, therefore reducing it.

Figure 4 also indicated that in presenting the impacts of all sub-systems in the one graph makes it difficult to decipher what is happening within the sub-systems, and therefore Figure 5 depicted a sample set of results for BFS and LHR. This Figure demonstrated further the influence of cancelled flights and the number of elements within systems. Cancelled flights were seen to cause increases in impact whilst increasing numbers of elements within the sub-system could cause increases or decreases depending on the number of newly cancelled flights.

The system impact, Figure 6, showed that with the aid of impact maps that it is possible to gain an understanding of what is happening in the system at a given point in time.

It was pointed out that the ash cloud boundary did not, in many cases, demonstrate a difference between each side. This indicates that weather maps will not provide the ability to visualize or predict what is happening at airports within it as there are other influential variables.

The volcanic disruption has highlighted the following points:

- It is difficult to accurately model complex scenarios due to the real system characteristics of human-in-the-loop and exposure to uncertainties.
- In any real world scenario there will be delays due to unforeseen circumstances which are not currently modeled in the impact analysis tool and it is debatable as to whether it is inherently possible to do so in any model.
- The number of elements within a sub-system is highly influential on the impact on it.
- Cancelled flights are influential on the sub-system impact
- When viewing sub-system results it is better to view them separately or in small numbers to make it possible to understand what is occurring.
- Complex scenarios lead to complicated impact distributions

B. London Heathrow closure

This analysis presented 4 different scenarios; short closure, short closure with diversions, full day closure and fully day closure with diversions at LHR.

The results output by the short closure scenario showed that even with LHR not permitting aircraft landing or taking off the other airports experienced what resembled generic impact noise. In any traffic system of such a size there will be small delays ranging from a passenger being late to the fuel being loaded. These incremental delays induce what can be described as impact noise on the system. This in itself is worth commenting on as this impact noise is demonstrated in the other scenarios. This has introduced the possibility of a further impact level known as noise, which would make it simpler to identify behavior within the system hierarchy and distinguish between generic noise and actual low level impact.

Returning to the results, the closure of LHR was for a period of 1 hour which means the most any aircraft should have been delayed will have been an hour which will not create a high impact on the flight let alone the sub-system. Therefore this closure will have introduced small delays on to a number of flights and due to the large capacity of the system it is easy for this impact to be absorbed at the sub-system level. This is emphasized by the impact at LHR returning to a low level upon the end of the closure demonstrating minimal delays to any aircraft within it. Furthermore an airport such as LHR which has been modeled with two operational runways will be able to respond faster than those with one, especially during slow traffic periods.

In the short closure with diversion scenario the results indicated that, unlike the previous scenario, other airports are impacted while LHR is closed. These airports experience a medium level of impact for a short period of time which arises from flights due to depart to LHR which must be diverted due to the closure. Once these flights take off the impact they have incurred from the diversion is absorbed into the impact noise again due to the large number of flights within the system. Any flights due to depart LHR are delayed during the closure period but, as with the closure scenario, any delay is minimal and does not increase the impact at any location to anything other than low, absorbing it within the noise. This scenario has demonstrated that for such a short period of closure it is pointless to divert any flights as this will create an impact on any airports with outbound flights to the closed airport. It must be noted though that the impact post-closure experienced in both is similar.

The third scenario invoked a closure of LHR for the full simulation. This closure caused 6 of the 7 other airports to become highly impacted after the simulation started, with occasional fluctuations to medium. Each of these airports ended the scenario with high levels of impact. With the shorter closure each the flights at LHR both inbound and outbound were delayed, but in this case the flights are cancelled. A cancelled flight corresponds to an inoperable level of impact. Therefore those UK airports operating multiple, daily low cost flights to LHR are

impacted, which explains the high level of impact experienced by ABZ, BFS, BHD, EDI, DUB and MAN. As cancelled flights never take-off from their origin airport they never leave the system, hence the impact remaining high at the airports at the end of the simulation. The fluctuations experienced by the 6 airports during the simulation arise from other flights operating as normal which decrease the sub-system impact.

In the final scenario the impact level never exceeds medium but at each airport it can be seen to fluctuate rapidly throughout the duration. In the short closure with diversion scenario very few aircraft will have been diverted, but in this case there is 18 hours worth of LHR bound aircraft to be diverted. This larger number of diverted aircraft increases the impact at each of the airports and causes them to fluctuate as the aircraft move through the system. As the flights are not cancelled like the previous scenario they do not increase the impact beyond medium. With all aircraft completing flights, even if different airports, the impact at all open airports returns to nominal prior to the end of the simulation. This is also due to the impact tool not imposing an impact penalty on the destination airport of cancelled flights though this is currently being implemented. LHR remains closed and therefore inoperable.

In the Results section, it was identified that LGW experiences no impact level above low for all scenarios even though it was the destination for flights diverted from LHR. This arises from:

- LGW outbound flights are unaffected
- The flight data was collected in April and therefore not during a time of peak traffic
- LGW has two runways to cope with the excess traffic
- LGW has a larger flight throughput than the other airports (excluding LHR) and therefore impact is absorbed easier.
- The diverted flights do not all arrive at the same time, rather periodically throughout the day again improving impact absorption

With the impact levels being similar for LGW across the scenarios it was deemed necessary to present another set of results; the computational impacts for LGW. These were compared graphically in Figure 11 and illustrated the difference in impact experienced by LGW. This highlighted the closure with diversion scenario to have impacted LGW the most due to increased inbound, diverted flights. The second highest was the short closure with diversion which arises from a small number of diverted aircraft landing at the airport. The closure scenario was next followed by short closure, with any impact arising from minor flight delays.

Only 10 of the 21 airports were represented in the results for the LHR closure due to the others not being impacted beyond the generic noise of the system. The majority of the unaffected airports are too close to operate a route to LHR. It is also notable that those airports that were impacted operate low cost daily flights to and from LHR.

The final set of results presented, in Figure 12, are the system impacts for each of the scenarios. This showed the closure scenario to have the biggest impact on the system with a medium impact for most of the duration. This highlights the large traffic throughput and the importance of LHR within the UK airspace. With the airport inoperable and all inbound/outbound flights cancelled this creates impact on a number of the airports that now have stationary, inoperable impacted flights. If a smaller airport had been closed the system impact may not have reached this level.

The other scenarios show system impact of either nominal or low, though each maintained a low impact for much of the simulation. The full day closure and divert scenario is the only of these scenarios not to return to a nominal level due to the continued closure of LHR. The short scenarios return to nominal as expected due to all aircraft having landed and the closure of LHR being over.

These results demonstrate that there is little difference between the two short scenarios. The short closure scenario does fluctuate more between nominal and low indicating less impact during the simulation. This would suggest that either delaying or diverting is suitable for a short period of closure, though it was indicated through the sub-system impacts that diverting flights will cause larger impact for short periods at other airports. It must be noted that this is a single day analysis and therefore there is no impact penalty for the aircraft being in wrong location for the next day's flights which would create a difference between the short scenarios.

With regards to the two full day scenarios, the impact results clearly show the system is less impacted during the closure and divert scenario. This suggests that for a full day closure it would be better for the system to divert aircraft to the nearest airport as this reduces the overall number of cancelled flights. This does incorporate the assumption that the nearest airport has the capacity to cope with the added traffic. As with the short scenarios, there is no impact penalty on the aircraft being in the wrong location.

The London Heathrow closure analysis has highlighted the following points:

- It is possible that a new impact level should be introduced to represent impact noise to distinguish what is generic system behavior and what is actually low level impact.
- Within the complex UK ATM system the large volume of traffic increases the likelihood that short delays due to closures or other issues can be absorbed in the impact noise.
- There is not a substantial difference at the system level between delaying or diverting aircraft for the hour long closure, though the difference is present at the sub-system level.
- For long closures, diverting the aircraft creates less impact at both the system and sub-system levels suggesting this to be the best approach given the assumptions made.
- The number of elements within a sub-system is highly influential on the impact on it.
- The capacity for traffic throughput at airports influences its ability to absorb impact.

It is notable, that with the exception of the first point, that these are logical conclusions to draw with regards to the real system. Furthermore, those discussing when to divert, delay or cancel allude to already practiced protocol.

VIII. Conclusion

It is difficult to understand or predict the behavior of complex systems due to their associated characteristics, and whilst a number of approaches have been developed, they tend to be time consuming, costly and data intensive. This paper has presented an impact analysis and its associated methodology which can be used to analyze complex systems whilst being simple, qualitative and reducing the computational burden. The approach identifies elemental relationships and interdependencies and analyses the impact of one element on any or all of the elements within a system.

Two analyses have been performed using the model and these have demonstrated that it is possible to understand more about the way the sample ATM system operates, and how its behavior evolves through the scenarios.

The volcanic disruption analysis was the first to be presented and showed good correlation between the simulated results and those from the real system, though there a small number of anomalies. The reasons for these were determined as being:

- Inaccurate input data
- Inaccurate scenarios
- System protocol
- Human-in-the-loop
- Uncertainties

The human-in-the-loop and uncertainties are characteristics of the real world system and are difficult to emulate from a modeling perspective. These characteristics become prominent in complex scenarios such as the ash cloud event as they require multiple human decisions based on dynamic information. This model is designed to be simple, qualitative with a reduced computational burden and modeling such characteristics would violate these criteria.

Therefore research is ongoing to recreate less complex scenarios captured from the real ATM system to further validate the approach.

The other causes of the anomalies required simple modifications to the model or further research into acquiring more accurate data sets.

The London Heathrow closure analysis identified what has been described as impact noise which is generated by generic minor delays in the system causing low impact at the sub-system level. This has introduced the possibility of another impact level being introduced to represent noise to distinguish between the generic system behavior and low level impact.

Furthermore the number of elements with a sub-system, and the capacity of traffic throughput at the airports are highly influential in absorbing impact. Cancelled flights, on the other hand, are influential in emphasizing system impact.

The short scenarios in this analysis highlighted that when an airport is closed for a short period of time the impact arising from this can be absorbed in the impact noise due to the large volume of traffic. For long closures the impact is lessened when the inbound aircraft are diverted given the assumptions made. For short closures diverting the aircraft makes minimal difference to the system impact though it will impact a number of airports at the sub-system level.

Both scenarios have indicated a number of points which will be implemented with further research:

- Cancelled flights must impact their destination airport.
- If running scenarios longer than one day, there must be an impact penalty for the aircraft being in the wrong place and the alteration in its fuel consumption.
- The current data means all flights are assumed to have a corresponding aircraft which is not true for the real system. The aircraft will have a number of flight routes/numbers over 24 hours and therefore matching aircraft to flight numbers would improve the accuracy of the model and allow simulation of rolling delays.

In conclusion the model and approach have been assessed through the two analyses which have emphasized their potential and capability with regards to understanding more about how a complex ATM system operates and how its behavior evolves through the scenarios. The use of an agent based impact analysis has been shown to identify elemental relationships and interdependencies in a simple, qualitative and data non-intensive manner. The research has identified potential modifications to the model, corresponding protocol and data extraction. Furthermore future areas of research have been established including modifications to the model to improve its fidelity and the potential for implementation of a noise impact level.

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