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# ENHANCING THE TOOLKIT OF AIRPORT OPERATIONS ANALYSTS: EVIDENCE FROM AN AIRPORT BAGGAGE HANDLING SYSTEM IMPROVEMENT PROJECT

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## ABSTRACT

We discuss our experience from helping an airport operator and their team of airport operations analysts to introduce discrete-event simulation alongside their existing system improvement/development toolkit. Our project looked at improving the existing baggage handling system of a major European airport run by our partner organization. This paper is divided into two separate but related discussions. First, we collate recent reflections from this project together with those from similar airport projects we have been involved in for the past decade. We discuss a few observations that we believe should help to convince airport operators to develop more in-house skills around both analytical and simulation modeling and analysis, with a focus on the latter. Secondly, we describe one of the simulation components of our baggage handling project and demonstrate the effectiveness of various possibilities to improve the availability and reliability of these systems when operating under tight capacity constraints.

## 1 MOTIVATION

Airport operations and processes have always been on the radar of the simulation community, from the early days of the Winter Simulation Conference, see e.g. (Robinson 1969), (Lui et al. 1970) or (Seeman 1970), and beyond, see e.g. (Baron 1969). And they are still of high interest, as shown by recent publications such as (Zhang and Mahadevan 2017). Significant figures and adverse reports of various nature periodically surface in the news around how badly things can go when airport operations experience major disruptions, see e.g. (DailyTimes 2016) and (CAA 2016). Analogue figures are often cited in the opening sections of many scholarly articles; we ourselves have contributed to the debate - see (Tomasella et al. 2016).

Despite the above, a good number of airport operators we have worked with in the UK/Europe in the past decade have shown a general lack of practice of OR-grounded techniques, including simulation, in their system/process improvement processes, whereas, in fact, for mid- to large-sized airports (say from a few million up to a few tens of million passengers per year), one would always expect that airport operations analysis teams would include OR graduates. Although this is often the case, it is also frequent to find the typical composition of skills and toolset within airport operator organizations to feature little to no OR background, methodologies and software. On the contrary, members of airport operations analysis teams at many airport operators tend to come from either mainly qualitative backgrounds, including qualitative operations management, from related fields such as six-sigma/lean manufacturing, from airport/aviation engineering, or, finally, from other types of quantitatively-orientated analyst roles (e.g. financial, statistical). Whilst these backgrounds certainly play an important role in airport operations analysis teams, we believe

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both analytical and simulation methodologies from OR may be conveniently adopted to enhance the results of airport improvement/development projects.

When faced with a process improvement project, teams of analysts like those we have collaborated with generally limit themselves to perform: static analyses of overall system requirements (e.g. number of outbound bags to be processed in an hour, number of passengers to go through security in 15 minutes, etc.); basic system performance analyses (e.g. bottleneck identification) in *steady-state* conditions (something largely unknown to airport operations!); and basic statistical analysis of performance data collected from the field. We found that very little to no modeling, whether analytical or simulation, was performed. For the detailed study (if any takes place) of dynamic aspects of the system under improvement, these airport operators would most often resort to either the services of external consultants or to having to trust the results of the simulation analyses performed by system vendors (Wu and Xie 2017). Needless to say, the latter approach especially entails a number of potential project related risks (vendor bias, overengineering, unreasonably high investment costs, etc.) that could actually be minimised, if only airport operators were able to control larger portions of the development and analysis process.

The rest of this paper reports more specifically (unless otherwise stated) on one of these projects we recently completed, where we worked with the operations analysis unit at a major European airport. Our improvement project was centred around enhancing the operational resilience of their baggage handling system (BHS). The following pages have a twofold purpose: (1) to discuss the learnings in terms of simulation methodology and practice generated by this and related experiences and deemed transferable to other realities where simulation modeling and analysis of airport operations is required and not yet adopted; and (2), to discuss the learnings from this particular project that are related more in detail to the operation of airport BHSs and have not been reported yet by the research community. Section 2 provides a high-level background context. Section 3 discusses how simulation modeling and analysis skills and tools can enhance the typical airport improvement/development project, especially when either carried out or at least largely controlled by the airport operator. This section is intended for practitioners from airport operations analysis teams who have little familiarity with simulation/analytic modeling and analysis. Section 4 addresses both researchers and practitioners, and discusses the results from one of the phases of our simulation work, where we developed and tested the first elements of a Java library for discrete event simulation of airport operations. Specifically, we discuss a number of possible avenues to improve availability and reliability of existing BHSs in the face of tight capacity constraints. Section 5 concludes the paper.

## 2 PROJECT CONTEXT

Recently, an airport operator we were working with revealed to us their intention to introduce simulation, potentially in combination with other OR methodologies, in their business development and operations analysis teams across the airports they operate. The opportunity came with the need to redevelop the BHS at an airport they had recently acquired, which at the time was experiencing dramatic capacity constraints whilst undergoing a major expansion programme of their terminal facilities. While the longer-term goal was to develop the future BHS for the considered airport, in the shorter term they aimed at making the current system viable for peak operations of the following summer season. This was some nine months away, including all needed system modifications, deployment and testing before ‘going live’.

The project team included us, as an academic partner, the airport operator, and two prospective system solution providers. It was immediately self-evident that an interesting mix of simulation approaches were being made available from around the table, from which the airport operator wanted to exploit the knowledge created within this project to develop a comprehensive simulation modeling and analysis approach to be adopted in the future. The airport operator brought to the table their direct experience from recently acquiring a package for three-dimensional (3D) modeling and simulation of airport operations. At the same time, each of the vendors showcased their system solutions by using various simulation tools, ranging from general purpose simulation software to their own, in-house developed simulators.

Finally, we added to the group our own, vendor independent, expertise in simulation. We adopted two parallel simulation approaches, by: (a) developing an independent simulator of the as-is BHS at the given airport, by using a commercial off-the-shelf product; and (b) developing a fully functional library for the simulation of all components of an airport BHS. With respect to (a), we developed a simulator using Rockwell Arena, featuring two-dimensional (2D) animation, for no particular reason other than because no other project partner was using Arena. With respect to (b), we extended SSJ (Stochastic Simulation in Java), an existing, well-known, java library (L'Ecuyer et al. 2002) for stochastic simulation, which was augmented with capabilities to simulate conveyor belts, sorters and other physical and logical components typical of airport BHSs. SSJ was chosen among the many java libraries available for simulation largely because of the extensive facilities available in it to deal with random number generation. The approach in (a) served two purposes: (1) to validate results from the models created and used by the vendors, as well as to help the airport operator validate their own 3D model of their as-is BHS, as this was being built; and (2) to help the airport operator to understand some of the differences in functionality existing between airport-specific and general purpose simulation packages, to inform their future software choice. We added the approach in (b) to show the airport operator an alternative approach to simulation, and demonstrate the likely differences in costs (software licenses, model building and validation, animation capabilities, etc.) as well as in the skillset required of new airport analysis recruits to work with these approaches and tools.

## 3 AIRPORT SYSTEMS IMPROVEMENT/DEVELOPMENT

Figure 1 shows the sequence of phases any airport system improvement/development project can be broken down into. Asterisks identify those phases that we have found to be carried out directly by airport operators we have worked with in the past; we found the other phases to be typically outsourced to either independent consultants, researchers, or system solution providers. Figure 1 also maps the data used and likely software tools employed in each phase. Brackets represent optional or less typical use of software.

This process presents all the elements of a typical *hybrid simulation/analytic modeling and analysis process*, which (Shanthikumar and Sargent 1983) defined as: *Hybrid simulation/analytic modeling consists of building independent analytic and simulation models of the total system, developing their solution procedures, and using their solution procedures together for problem solving*. This broad approach to modeling has been developed over the years in many sectors, e.g. manufacturing, and have been extensively reviewed, recently in (Figueira and Almada-Lobo 2014), (Fu et al. 2015), (Eldabi et al. 2017), etc.

Following section 2, in this section we first observe that either type of modeling is hardly carried out by airport operators, and, when adopted, it is mostly outsourced to system solution providers. Our qualitative argument in this section is that were airport operators willing to carry out a larger portion of the process in Figure 1, and to develop the needed skillset within their operations analysis teams, they would achieve appreciable benefits, as compared to their current way of proceeding, most prominently: (1) better control of project costs and risks; and (2) a more comprehensive approach to the creation, sharing, use and management of system/process knowledge within the airport analysis team.

Airport operations analysis teams generally focus on Phase 5 (Performance Monitoring / Continuous Improvement), where they apply continuous process improvement and other related tools. Decision making in this phase is informed by the use of performance dashboards and a wealth of historical data collected from the field, including data sets generated by ad-hoc performed field trials. These trials are almost never performed as a series of designed experiments, which in itself is often enough to invalidate the conclusions obtained in cases where process knowledge and intuition fail, as no rigor is applied to the experimental effort. Design and Analysis of Experiments (DoE) skills (Montgomery 2008) would benefit field trials in airports just as well as they are doing in other fields of enquiry.

Beyond the obvious costs of running these experiments (materials, personnel, etc.), an additional problem of field trials in airports is that it is not always feasible to stop the system under study (including BHSs) for the sole purpose of executing the experiments. The simulation community - see section 1.1 of

(Law 2015) - has long suggested the use of simulation as a means to aid continuous system improvement on a regular basis, an advice that only very few airport operators seem to have taken on board.

Airport systems also undergo major re-designs, e.g. because new technologies are mandated by regulatory bodies (in BHSs this happens every time new risk emerges or superior technology for automated baggage screening is developed) or because major system components are reaching their natural end-of-life term. An airport system may also have to be developed from green field, with investment costs that easily reach the tens of million $ or even higher figures (depending on the system). We found that the role of airport operators in design/re-design projects tends to be quite *passive*, from a modeling and analysis perspective, and taken up by external suppliers from very early on in the process. There may be an initial round of workshops or presentations from suppliers, one of which gets selected to develop and propose high-level options for consideration by the airport operator, before resources are committed to the development of the preferred system design alternative. These suppliers are expected to provide the airport operator with the following pieces of information: (1) high-level specifications of the proposed configuration options, including e.g. technical drawings; (2) estimates of the operational performance of each option, particularly at peak times; (3) some form of quantitative, more detailed, analysis of the dynamics and related performance of the selected high-level option. As mentioned in the opening section of (Wu and Xie 2017), providing the latter normally involves discrete-event simulation.

In our past projects, we have witnessed most external suppliers taking the following approach. First, they generate high-level options, e.g. see Figure 1a in (Wu and Xie 2017), based on either templates from their own product portfolios and/or rules of thumb available from industry publications, e.g. (IATA 2004).

Then, rough estimates of static/steady-state performance are presented to the airport operator through simple electronic spreadsheets, with capacity figures, e.g. bags/hour processed, discussed over a number of passenger growth scenarios provided by the airport operator itself. Spreadsheets formulae employ simple rules of thumb and typically no analytical modeling (e.g. queueing models) is used, despite their availability from an extensive literature - see e.g. (Leone and Liu 2005) for an analytical model related to BHS design.

Finally, once the preferred high-level option is selected, a detailed design is produced by the system provider and analyzed through discrete-event simulation. Suppliers use 3D animation to validate the flows of entities through their model. Results are then produced through a number of 'experiments', which we have found being affected by two main issues: (1) DoE is virtually never employed, which may affect the validity of the analysis and related recommendations; (2) most of these 'experiments' constitute *largely deterministic* simulations, in that for instance failures and repairs of system components (e.g. conveyor belts in BHSs) are not modelled/analyzed, and where often the inter-arrival processes of the entities of interest (e.g. of passengers/bags) is modelled as a deterministic parameter.

We believe that by embedding OR skillsets and tools within their teams, airport operators may be able to take more control of phase 2 of Figure 1 and hence of the generation of the system configuration alternatives to be included in the analyses. Rigorous methods are available - see e.g. (Fu et al. 2015) - to guide OR-informed airport operators through a more thorough exploration of the space of possible design alternatives. This may lead them to discover potentially promising design alternatives that would go otherwise unnoticed if only informed by rules of thumb reasoning. OR graduates would be able to pick up existing tools available from the literature and customize them for prompt use; one single such recruit alone will significantly boost the capabilities in the team. On another note, the potential number of system improvement/development projects that any airport of a reasonable size would run in a year where modeling and analysis is needed (Phases 3 and 4) is unlikely to be small, hence the investment in internalizing OR modeling and analysis skills and tools should easily pay-off once implemented rigorously. While system solution providers will eventually deliver a working turn-key solution to the airport operator, the interests at stake are too high to simply let them take the lead on the crucial modeling and analysis tasks. It is in fact through these tasks that the actual return on investment from each project will be determined.

A final discussion regards more closely the simulation component of airport improvement/development projects. 3D animation capabilities, as available in many existing software packages, both general purpose

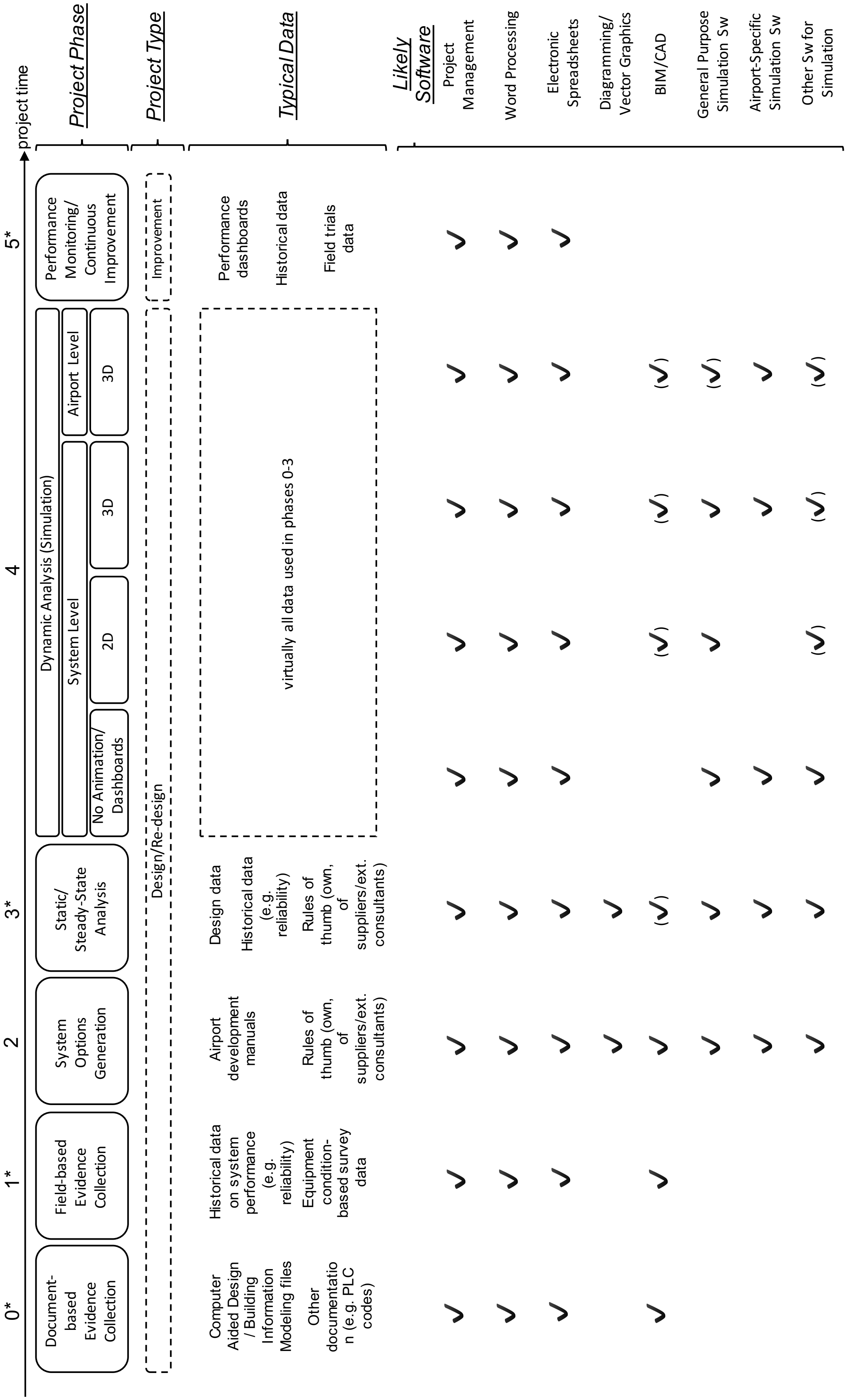

Figure 1: Phases, data and software involved in airport system improvement/development projects.

(Automod, Simio, etc.) and airport-specific (e.g. CAST or ARCport), appear to be sometimes misperceived by airport operators as the core functionality of the software product of choice for them to be able to perform simulation studies. A distinction should be made at this point between simulations performed at the level of the single system *vs.* those carried out at the airport level.

Most airport improvement/development projects happen at the system-level (e.g. check-in concourse re-design, gate allocation improvement). In this context, simulation can be approached in many ways, not all of which require extensive animation capabilities from the simulation package in use. We will discuss in the next section a possible approach, based on a general purpose programming language such as java, where no visual animation is provided but where, at the same time, other features are made available, such as ease of integration within simulation-optimization methodologies, with respect to which existing commercial simulation packages provide much less flexibility. Whilst 2D animation of bag, cargo, passenger and aircraft movements is often included by simulation modelers, it is also not always essential. In many cases, we have found simple dashboards of operational performance indicators to be enough to guide airport operators in their decision making. These may take the usual forms of counters (e.g. total number of bags entering the BHS from a specific check-in desk) or graphs (e.g. time series plot of the number of passengers being processed by a given security lane every 15 minutes) to be displayed at run-time, recorded in a video, and then discussed in a session with the simulation project champion. Finally, in the last phases of the simulation study, having a comprehensive 3D animation for the system will ensure that other aspects related to the feasibility of the developed solution, such as how well the BHS system fits within the existing building space, constraints, etc., can be tackled. Operational performance analysis is typically already concluded at this stage, well informed by the 2D/dashboard-based simulation models and possibly enhanced by analytical and optimization models from earlier phases, particularly phase 3.

Finally, airport level simulation tends to be tackled directly at the 3D level, its purpose being mainly that of providing the airport operator with a synoptic view of how aircraft/passenger/baggage/cargo flows interact within the airport as well as with the nearby infrastructure (e.g. access roads, railways) for better understanding of possible operational issues that cannot be picked up by looking at single systems in isolation. Practitioners who are new to simulation and interested in additional practical advice can find more general accounts of the above discussions in the literature - see e.g. (Jurishica 2010).

## 4 CASE STUDY

In this section, we extend the discussion on operational resilience of airport BHSs we initiated in an earlier paper (Tomasella et al. 2016) and report some novel results on automated logics for airport BHS dynamics.

### 4.1 Airport Baggage Handling Systems

A typical airport BHS layout (see Figure 2) generally comprises a number of parallel interlinked conveying lines (e.g. the set of conveyors $L^1_1, L^1_2, L^1_{3,S_1}, L^1_{3,S_2}$ represents "line 1") that route bags from the check-in concourse, via check-in desks ($d_1,\ldots,\ldots,d_I$), through X-ray screening machines ($H_1, H_2, H_3$, though there may be more) through to sorters ($S_1$ and $S_2$), up to reaching, via chutes ($C^i_j$) so-called flight make-up positions (MUPs). These are fixed positions identified on the floor of the BHS hall and assigned to outbound flights, where bags are arranged in containers (trolleys, unit load devices) for transfer to their flight.

Flexible routes through the system are realized in three main ways. Firstly, a number of bi-directional conveyors (altogether called the "collector line", see $b_1,\ldots,b_B$), located immediately downstream the check in desks, make it possible, in principle, to direct any bag from any desk to any of the conveying lines. Secondly, one or more conveyors (see $l_{1,2}$ and $l_{2,3}$) may exist to provide cross-links between the main lines for additional routing flexibility. Finally, vertisorter mechanisms split the baggage flows from each line, immediately downstream the X-ray machine, depending on the destinations chute, by sending bags to different branches - e.g. vertisorter $V_1$ routes a bag going to chute $C^1_1$ on sorter $S_1$ to branch $L^1_{3,S1}$ of line 1. Altogether, the three mechanisms enable a fully flexible routing from any desk to any chute.

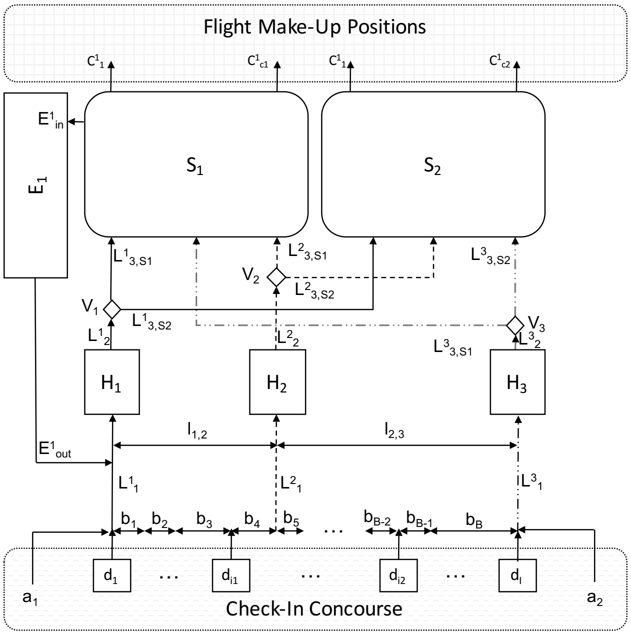

Figure 2: A very common BHS layout.

A frequent characteristic of BHSs is the presence of Early-Bag Stores (EBSs, see $E_1$). These allow passengers to drop their bags as soon as they arrive at the airport, even if MUPs for the related flight are not yet ready to use (e.g. because still in use by another flight). Floor space for MUPs is commonly a scarce resource in airports operating under capacity constraints. Entry to an EBS is typically provided through dedicated chutes from the sorters ($E^1_{in}$) and re-entry routes to the system are typically channeled through dedicated lines ($E^1_{out}$) back into one or more of the main conveyor lines (line 1 in our example).

When operating under tight capacity constraints, during peak-days, the airport may also experience a shortage of check-in desks. In such cases, mobile desks are set up in the check-in concourse to accommodate the additional outbound passengers. Bags processed at these desks get transferred manually to the BHS - see points of entry $a_1$ and $a_2$. More details on BHSs and their role within the overall airport baggage handling operations can be found in Chapter 7 of (Ashford et al. 2013).

## 4.2 Problem Statement

The BHS we studied had a layout similar to Figure 2 - more specific details, such as the total number of chutes available, are intentionally omitted, as they do not affect the rest of our discussion but also to protect the identity of our project partner. This part of our overall project looked at improving the operational resilience of our BHS, which was experiencing excessively many and long stoppages of its main lines, with significant drops in overall system availability over the day of operation. With capacity being fixed in the short term (re-design of the BHS was under way), and the number of flights at the given airport increasing, following Summer operations were deemed unsustainable. Shortage of MUPs as well as finite capacity of our two sorters meant that our three main lines would often be unable to send bags to the sorters. This was causing bags to die-back (queue, effectively) towards the screening machines and the collector belt, ultimately reaching the check-in desks. At that point, bag drop operations would halt and, more importantly, the previously hidden problem would surface and reveal itself to passengers. The concourse would then quickly fill-up with angry passengers, now worried of missing their flight. In the era of social networking, this meant unnecessarily putting the reputation of the airport at risk. Reliability problems were adding up to the issues impacting system availability. With most of the equipment being close to its end-of-life, additional die-back of bags was being caused by more frequent failures of conveyors and other components. We then worked with the airport operator to enhance the dynamic capability of their BHS in responding more effectively to the inevitably frequent occurrence of die-back. We decided to focus on the development of alternative system logics that could exploit the inherent routing flexibility of their system, together with other ideas for improvement, to help the system to recover more quickly from a die-back situation and, first and foremost by stopping die-back from reaching the check-in concourse. Our simulation study then assessed the potential from a number of identified alternative interventions before the best option could be developed into the system's Programmable Logic Controllers (PLCs), tested and deployed for operation.

### 4.3 System Modifications under Study

The existing, or *as-is*, BHS logic was based on pre-arranged routes of bags from a given desk through a given line, sorter and chute, and on BHS human controllers to manually adjust these routes when needed, typically when die-back of bags would build up on one of the main lines and reach back to the collector belts, thereby stopping the related main line.

With respect to the *as-is* logic, our identified first option differed in that instantaneous change of direction of the conveyors on the collector line would enable a prompter re-routing of bags from desks into the main lines. This direction change would be initiated remotely by manual command from the control room. Under the as-is logic, the same change of direction could also be enacted manually by the BHS controllers, but locally to each conveyor on the collector line. One change of direction for a single belt on the collector line would take up to about 15 minutes under the as-is settings. On a 0-3 scale of increasing effort related to change in logics and PLC coding, we called this first option *level 0* logic. In practice, even level 0 changes would be costly, as documentation related to PLC code and logic had never been made available by the former airport owner and PLC technology was about 20 years outdated!

Our second option, or *level 1* intervention, was based on a more pre-emptive measure, whereby a die-back reaching the X-ray machine of any of the main lines would stop bags from the collector line to access it, until the resolution of the die-back. During this time, bags originally bound for the disrupted main line would be re-routed to other lines, via changes in direction of the conveyors on the collector line, which would happen instantaneously and remotely, at the controllers' commands, as in *level 0*.

The next option, or *level 2* logic, employed instantaneous changes of direction of both the collector belt conveyors and of conveyors $l_{1,2}$ and $l_{2,3}$, when die-back reaches the related belt junctions. In level 2 however, all these instantaneous changes were fully automated, with no interaction from BHS human controllers required. Depending on dynamic updates of the loads of each of the main lines, re-routings from one main line to another would then be enabled in level 2 logic.

The last option, or *level 3* logic, also looked at dynamic loading of the main lines, but differently from level 2 logic. Under level 3 logic, the number of bags injected from each desk every five minutes would be counted over time, and dynamic forecasts be computed (via standard forecasting techniques) to predict subsequent loads of the main lines, on a rolling horizon fashion. Automatic, instantaneous changes of direction of the conveyors on the collector line based on level 2 logic would then enact dynamic re-allocation of bags from the desks to the main lines, until resolution of the die-back caused disruption.

### 4.4 Simulation Approach

To the best of our knowledge, our operational resilience analysis of BHS operations is novel in the literature. The closest work to ours is (Wu and Xie 2017), who recently investigated a set of rules for optimal load balancing of BHS lines. Although related to our study of the logic we call *level 3*, the authors focus on the X-ray screening portion of a BHS and look at a specific BHS layout, while we look at the end-to-end bag journey and a more general system layout. A recent paper that helped guide our work is (Le et al. 2012), where the authors present a generalized set of operational performance measures for studying airport BHSs.

More inspiration came from case studies of BHSs subject to similar capacity constraints, such as (Cavada et al. 2014), and by simulation studies of PLC logic in airport BHSs, such as (Johnstone et al. 2007).

Within our project we chose, in conjunction with our partner airport, to tackle this investigation through a java-based simulation approach. For the reasons explained above, we developed an independent library for simulation of airport baggage processes, which represents the first step towards a comprehensive java library for airport operations simulation. Using our library, we developed a model of our as-is BHS and validated it against an Arena model, which in turn had been developed for another phase of our project and had been validated against the actual BHS.

Having based our java code on extending the SSJ library, our library enjoys in particular all the original features of SSJ linked to handling multiple random number streams within the same model. This is something we could exploit in our analysis and we could compare with respect to the random number generation capabilities of the Arena model. Our partner airport could thus experience differences in approaches both in terms of programming/model building as well as on more technical matters of simulation practice and appreciate their importance in generating rigorous results, as well as appreciate the differences in the efforts required by the two approaches. Random number streams in our java-based simulation included, in particular: (a) all inter-arrival times of different classes of passengers to check-in on different classes of flights (domestic, international short-haul, international long-haul); (b) all relevant failure modes for all the equipment in the BHS, with the related time-to-failure and time-to-repair distributions; (c) service time distributions for baggage handlers to off-load bags from chutes and load them into MUPs; and (d) service time distributions of both control and repair interventions from BHS human controllers to different elements of the BHS. A more detailed discussion is out of scope for the present paper.

### 4.5 Numerical Results and Analysis

As a sample of our results from this investigation, Figure 3 partially enables the comparison of our alternative PLC BHS logics in terms of three measures of performance: (a) average total number of failures per day; (b) average total time in a day spent in any failure mode; and (c) average daily availability. Results are displayed at the level of each of the three main lines and at the system level. By 'failure' we mean the state when the die-back on one or more lines has reached the check-in concourse.

Our results are based on 1000 independent replications and on a data set representing the single *peak day* of the following Summer and quite extreme scenarios in terms of bag/passenger ratio and mean times to failure and to repair of the many components of the system whose reliability was considered already problematic. Reliability distributions and related parameters were obtained and estimated thanks to an extensive system condition-based survey that one of the suppliers was instructed to carry out on the as-is system as part of our overall project.

Level 1 option outperforms all other options in terms of all three measures of comparison. Adopting level 1 logic could lead to up to 6% improvement on system availability with respect to the current BHS and between 1% and 2% with respect to the other alternative logics investigated. This would in turn yield a gain in system up-time of up to 72 min/day, with respect to the as-is logic, a result that was considered satisfactory by the airport operator, given the extremely demanding scenarios considered. Hence, anticipating the recovery effort through dynamic re-routings enacted at a time when the build-up of bags caused by the fault is still far from reaching the check-in concourse represented the best choice for the BHS, at least until the new system was developed. This statement is particularly true for the main lines 1 and 3 of the BHS we studied, while for line 2 slightly better results in terms of availability of the specific line could be found by adopting the level 3 logic, something we could understand better once we had looked more closely to the different responses from each of the main lines to die-back events, including analyzing details from specific animations.

More precisely, we noticed that line 2 seemed to show only apparently a greater robustness, when compared to lines 1 and 3, to the heavily disrupted conditions of our experiments. In fact, although the average number of failures per day caused by die-back building up on line 2 appears to be much lower than those of lines 1 and 3, failures caused by line 2 last for up to 4 times longer. Closer investigation led to the understanding that sub-optimal allocations of flights to check-in desks were causing unnecessary overload to line 2. Again, additional evidence of the need to adjust check-in allocation especially by redistributing load currently assigned to line 2 can be seen in Figure 3(c), where line 2 appears to be the one that most benefits from the dynamic load balancing policy of the more sophisticated *level 3* logic.

## 5 SUMMARY

We started by reflecting on our experience of applying simulation to airport operations modeling and analysis and related suggestions directed to airport operators who are only now starting to venture into this territory. We focused on our recent experience of working on a BHS system re-design project, where a number of smaller projects was also carried out to improve the current BHS. We devoted the second part of the paper to discuss some of the novel results we obtained on one of these, where we analyzed options for the improvement of the PLC logic of the BHS to enhance its operational resilience. Future work will focus particularly on extending our java library for airport operations simulation.

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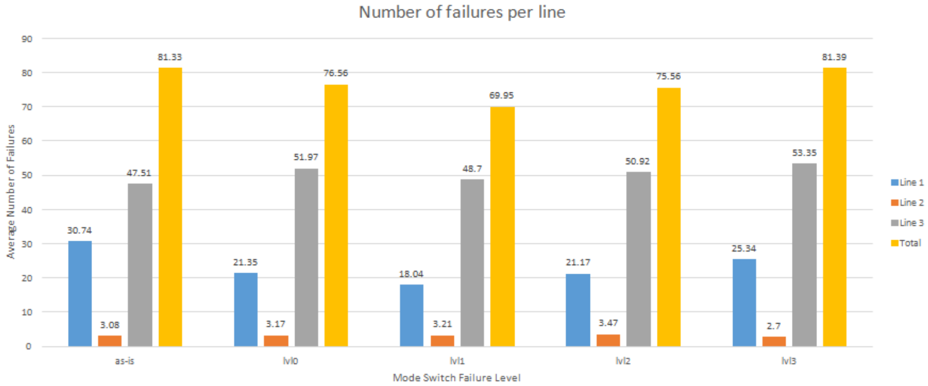
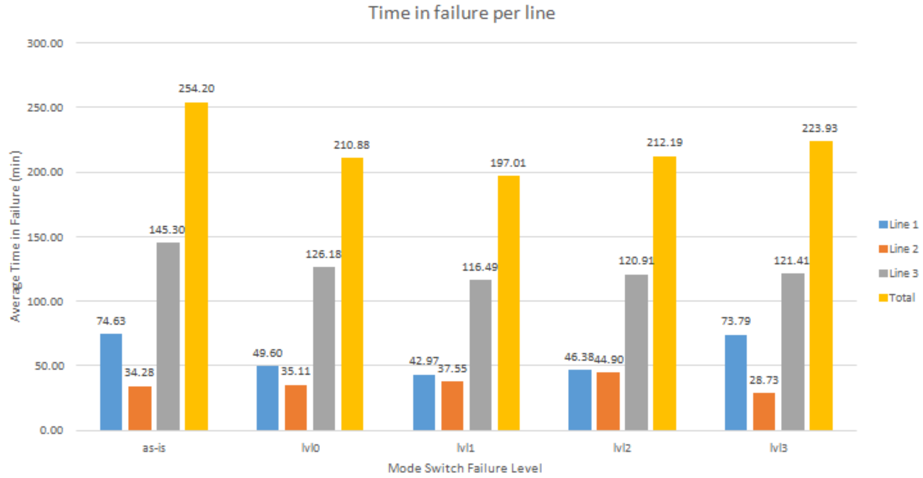
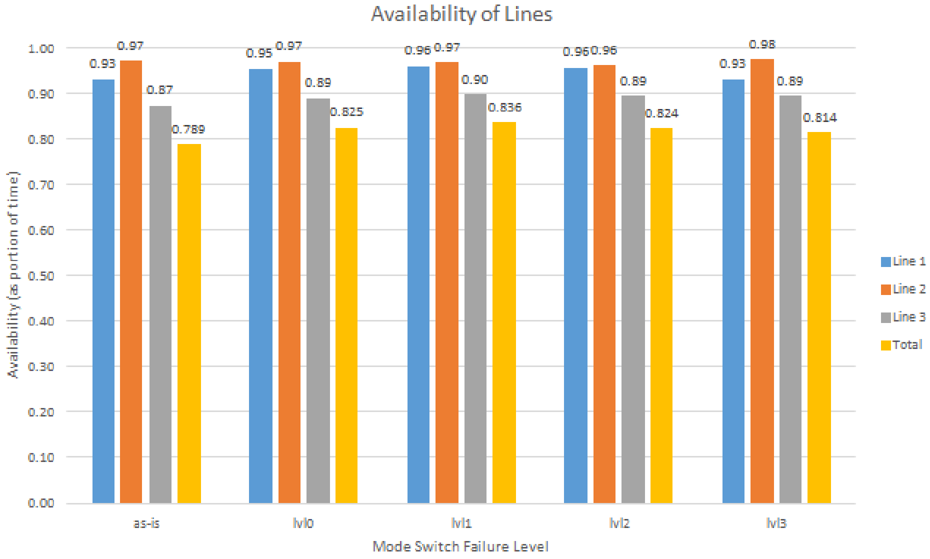


(a) Average number of failures per day (minutes)



(b) Average total time in failure per day (minutes)



(c) Average daily availability

Figure 3: Comparisons of PLC logic improvements for enhanced operational resilience

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