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1. Introduction

1.1. Context

- 1 Large-scale infrastructure projects such as new international airports inevitably exert influence on the evolution of the surrounding urban area. As the structure and configuration of the urban area changes, the flow-on effects are manifold and interconnected. To start, airports can usher in economic activity and employment on multiple scales. For example, Hakfoort *et al.* (2001) and Percoco (2010) distinguish between employment growth directly associated with an airport and employment growth that is indirectly induced by the airport. In addition, Peneda *et al.* (2011) put forth the existence of critical factors that are extraneous to the airport, such as its connectedness to the surrounding transport infrastructure and the economic potential

of the city itself. Freestone and Baker (2011) advise planners to unite both airport and city planning to ensure the integration of local interests within the larger-scale vision. They also propose that airports are a link between global considerations, national interests and local livability, adding to the complexity.

- 2 The benefits for employment and the economy need to be nuanced in relation to their geographical distribution. For example, the effect of an airport on property prices seems to be unevenly spread throughout the territory and influenced by the distance between the property and the airport. In general, the closer to an airport a property lies, the more its value benefits, however if it sits too close, it can be exposed to negative effects such as increased noise level (Tomkins *et al.*, 1998). The possibility of regional or national redistribution of growth rather than net economic growth on a broader scale, as highlighted by Hakfoort *et al.* (2001), also seems important to consider in the case of a second airport and its supposed complementarity or competition with the existing one.
- 3 Moreover, the impacts that eventuate depend on factors that change over the course of time. As often highlighted in academia (Pereira *et al.*, 2011; Freestone and Baker, 2011; Zietsman and Vanderschuren, 2014 to name a few), airport infrastructure requires a significant investment, with considerable impacts on land use, the environment and urban structure. In addition, none of these aspects are easily reversible. The state of the existing land use also limits the potential opportunities when planning a major airport project. Population and other demographic details combine with employment trends and the current state of transport infrastructure to influence the way an airport will interact with its territory. The demand for air travel is a crucial element that is constantly changing, yet exerts an immense effect on how an airport impacts the urban development of the city it services. In this context, planning, modeling and forecasting are crucial in order to reduce uncertainty regarding the overall outcomes of a second airport being built.
- 4 Thus, when it comes to the construction of a new international airport, timing is important. This study seeks to raise the subject of the effects on a city's urban structure that can come from delaying the construction of a major airport. More specifically, we examine the potential impacts on Sydney's urban structure that may have arisen as a result of delaying the construction of its second international airport from 1971 and 1986 to 2014. Several flow-on effects are also considered.

1.2. Airports as new urban centers

- 5 In his work *The Theory of Transport* (1894), Cooley asserts that urban growth often occurs at locations where there is a break in transportation (i.e. where travelers or cargo are required to change mode of transport to continue their journey). The nature of airports necessitates such breaks in transportation, thus they could be centers of urban growth. Appold & Kasarda (2012) have shown evidence of increased urban concentration around airports. Shapiro (2016) demonstrated empirically that Washington-Dulles International Airport is in fact serving as an anchor for the surrounding urban cluster. His research also found that the rate of urban growth within this cluster is linked to the airport's operations.
- 6 The relationships between airports and the cities they serve has at times been strained. A common historical grievance has been the noise pollution the associated flights bring

with them. As a result, airports were often located outside urban zones in order to mitigate this effect (Drummond, 1996). Cities have begun to place greater value on the proximity of airports as the importance of their accessibility and the economic enrichment they usher in has become clearer. Opposition persists in many cases due to noise complaints, including with the proposed expansion of Heathrow airport (Wolfe *et al.*, 2017). Kasarda coined the term *Aerotropolis* to describe a city that is spatially and economically centered around an airport. In fact, the Australian Government has used this term when referring to their plan for the zone around the new international airport under construction in the west of Sydney.

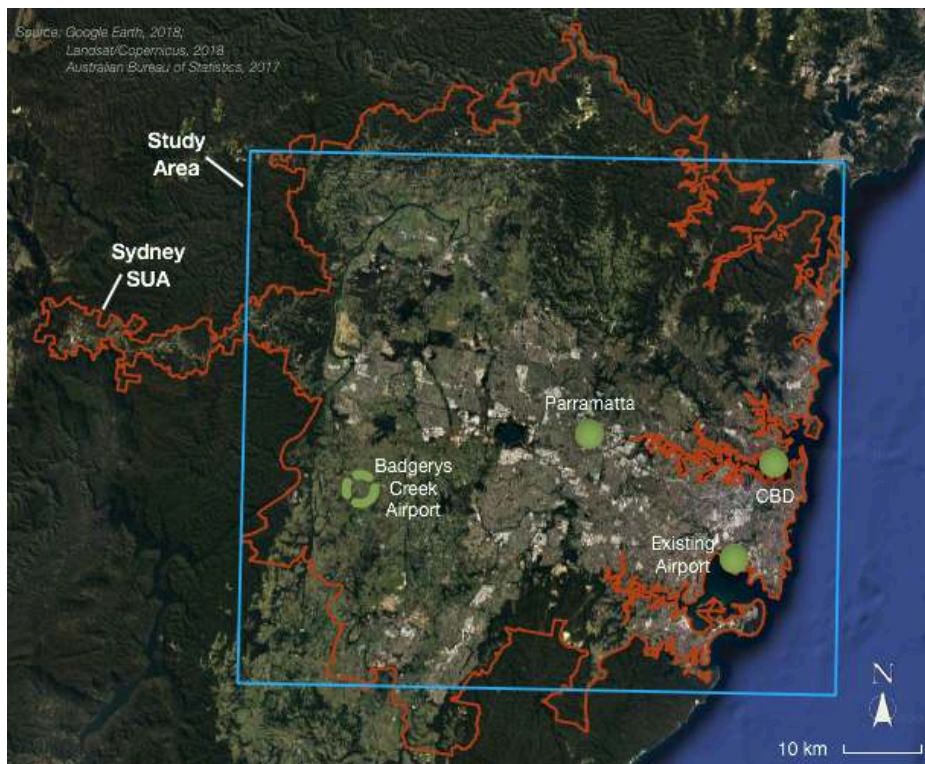
1.3. Sydney background

- 7 With a population in excess of 5 million inhabitants, Sydney is Australia's most populous city. The Marron Institute of Urban Management (2016) notes that the city possesses a population density of 25 inhabitants/hectare, placing it in the bottom 10% globally for cities with more than 500,000 inhabitants (Demographia, 2018). Despite this comparatively low density, Sydney has the highest population density of any Australian city.
- 8 Sydney's territory is predominantly marked by expansive urban sprawl while also containing a few zones of tall, dense development, especially in the Central Business District (CBD). Historically, the city expanded predominantly from the CBD outwards, however in recent decades the spread has been directed principally towards the west. This is due to environmental limitations in that the city has already spread almost to its environmental limits (ocean and National Parks) in the north, south and east.
- 9 Currently, the city encompasses one international airport, Kingsford Smith Airport (KSA), located in Mascot, 8 km south of the CBD (Figure 1). The airport's impact on the city is significant. In 2017, it was estimated to generate or facilitate AUD 38 billion of economic activity and the equivalent of almost 340,000 full-time jobs, equivalent to 2.2% of the nation's GDP (Deloitte Access Economics, 2018). As a result, it stands as one of Sydney's defining features, inevitably affecting the urban development of the city. However, a large portion of the influence KSA exerts on Sydney's urban form has actually been filtered throughout the city (Freeman & Tice, 2013). For example, much of the airport-related transportation infrastructure is now situated in Western Sydney; likely due to a combination of space constraints and cost considerations. This decentralized effect can plausibly be explained by its proximity to the CBD, its relatively high accessibility by highways and rail, and its surrounding areas being significantly urbanized. In 2012, it was forecasted that KSA would reach capacity by 2027 and the effects of overcrowding had already begun to be felt (Brown *et al.*). In order to meet this increasing demand for air travel in Sydney, it was announced that a second international airport would be built on a Government-owned greenfield site located in Badgerys Creek; an agricultural area 44 km west of the CBD. This study was conducted with these demand forecasts in mind, however the aviation industry has since experienced significant disruption due to the COVID-19 pandemic, so the forecasts are likely to be adjusted downwards.
- 10 The construction of a second international airport for Sydney in Badgerys Creek is not a new idea. It was first announced that a second international airport would be built for Sydney in 1971, with Badgerys Creek being one of eleven locations under consideration.

In 1986, the Government announced that the airport would be built at Badgerys Creek and acquired land soon thereafter. On both of these occasions, however, the project was repeatedly delayed and suspended (Williams, 1998). In 2014, after many more years of research and debate, the project was again announced, this time with construction starting in 2016.

- 11 For our purposes, the territory taken as belonging to Sydney is an approximation of the Sydney Significant Urban Area (SUA) as defined by the Australian Bureau of Statistics (2017). This was chosen as the most appropriate definition due to our focus on the greater city's urban development, however technical restrictions related to modeling required us to adopt a rectangular area that approximated this area (see Figure 1).

Figure 1: Satellite image of Sydney showing the study area used, the ABS' definition of the Sydney Significant Urban Area (Sydney SUA) and four locations pertinent to this study.



1.4. Objectives

- 12 This paper investigates the potential impacts on Sydney's urban configuration that could have arisen as a result of the deferral of the construction of the Western Sydney Airport from 1971 and 1986 to 2014. Today, Sydney consists of a relatively dense core (the CBD) surrounded by a sweeping, predominantly suburban expanse. This configuration has facilitated a high rate of personal car use (roughly 67% of trips) and significant east-west inequality in terms of accessibility and socio-economic status (Terrill *et al.*, 2017; Humi, 2005). It would therefore be of value to understand how the new airport could have impacted the distribution of accessibility, connectivity and urban density throughout the city.
- 13 To this end, we chose to build a model and perform simulations of urban growth in Sydney across various scenarios. The model we built incorporates Cellular Automata

(CA), Multi-Agent Systems (MAS) and networks to produce a land use map that evolves according to a number of variables. Our model drew significant influence from the urban growth model Raumulus, discussed in the next section. To allow for the calibration of our model, we used remote sensing to produce land use maps providing the genuine historical urban growth within Sydney, on the basis that the dynamics of future land use are likely to be significantly correlated with past trends. We then used these maps to fine-tune its parameters and ensure they were defined suitably. Having calibrated our model in this fashion, we then simulated the urban growth in the Sydney Basin springing from three different possible dates of construction for the new airport: 1971, 1986 and 2014. These dates correspond to the three years during which the construction of a new airport in Badgerys Creek was proposed or announced. We then simulated the potential urban growth of the city until 2054, thus modeling Sydney's past, present and future urban dynamics. It is this temporal aspect that is the distinctive attribute of this study. We propose the use of models based on time-series of this kind as effective instruments for exploring the potential impacts of new pieces of infrastructure on the urban dynamics of their surroundings.

- 14 We note that the primary orientation of this study is around urban development and not around the resulting environmental implications. The environmental considerations are important aspects that are worthy of attention, however they are not the focus of this study. Despite this, a reflection of the environmental concerns was given, however we attempted to not surpass what could reasonably be discussed in a study with this particular orientation.

1.5. Model background

- 15 Urban development within a city is driven by many factors of great complexity. Since this study covered the airport's effect on urban development across such a large area as the entire city of Sydney, the model created was formulated with a degree of simplicity so as to highlight only the principal general trends that may arise in the scenarios simulated. Consequently, it was able to assist with the identification and comprehension of some key dynamics at play across the entire city without being distracted by solely local dynamics. One key distinguishing feature of this study's modeling is the timeline used. Past development (the periods 1971–1986 and 1986–2014) was used to calibrate the model such that simulations produced urban development in a manner that was sufficiently close to the development that happened in reality. Following this calibration, simulations were performed for theoretical and future scenarios. Specifically, these scenarios include the urban development that may have occurred with a construction date for the airport of 1971, 1986 or 2014. The development was simulated from the construction date until the year 2054.
- 16 Our model was inspired by the model Raumulus (Reticular AUtomata Model for Urban Land Use Simulation), developed by Moreno, Badariotti and Banos (2012). Raumulus utilizes CA to simulate urban growth within a city. Moreno *et al.* demonstrated the capability of a model designed in this way to produce results that conform relatively well to a variety of urban structures and dynamics. The interdependence of elements within urban systems leads to complex dynamics that not all types of models are well placed to replicate, however, models employing CA are amongst those that are better equipped to handle this complexity. One other foundational aspect of Raumulus is that

it is oriented around the impact of urban centers on the configurations of the urban areas surrounding them. It also makes use of networks to simulate distance in a realistic manner – the distance along roads within the network. This aligned well with our premise of assessing the impact of a particular urban center (Sydney's second international airport) on the urban development of a real city. Other aspects from the model were also applicable for our usage, such as the impact of an area's urban density on its likelihood of urbanization. As such, given their suitability to our objectives, these elements from Raumulus were incorporated into the design of our model as well as its theoretical base.

- 17 The model visualizes a city as a grid of cells, each defined with a variable land use, overlaid by a network of roads. During each time interval, all non-urban cells are ranked based on the likelihood that they will be urbanized, then the land use definition for those most highly ranked are changed to urban. The likelihood of urbanization for a particular cell is calculated according to three factors: the distance to urban centers, the distance to the closest road and the urban density of its neighborhood. All of these details were conserved in the model used for this study. It does not take into account the complexity of some factors, such as the spatial organization of work, or detailed commute systems. A more micro-level approach with more details on the planning of the airport and the functioning of city systems would certainly be interesting. But considering the resources necessary, it was outside the scope of this study.
- 18 Our model considered three urban centers, taken from the Greater Sydney Commission's (2018) current metropolitan plan: A Metropolis of Three Cities. This plan envisions Sydney as having three major urban centers – the existing CBD in the east, Parramatta close to the geographical center, and the second international airport under construction in the west. Considering that one major goal of the metropolitan plan is to increase the proportion of the population living within 30 minutes of one of these urban centers by road, this figure (referred to as accessibility throughout this paper) was also tracked by the model throughout each of the scenarios.
- 19 When it came to the specific software chosen for the modeling, a number of factors came into play. Like Raumulus, our model makes use of CA and MAS; both of which have been shown to be appropriate for simulating urban growth (Chong & Jianquan, 2007). On top of this, our model set out to investigate accessibility, incorporating Sydney's road network, necessitating the use of software that could incorporate networks. As a result, a program called GAMA Platform was chosen due to its flexibility when it comes to incorporating networks into CA and MAS. GAMA is an environment used for producing object-based models, with a specially-designed programming language called GAML to facilitate this.

2. Method

2.1. Remote sensing

- 20 For the purposes of this study, it was necessary to obtain maps that provide a snapshot of the land use within Sydney's geographical bounds for the years 1971, 1986 and 2014. Armed with these snapshots, a model could be calibrated to allow for simulations and consequently a spatio-temporal analysis of the land use changes over this period. Unfortunately, while there were several sources containing land use data for 2014,

there were no viable existing options for 1971 or 1986. There was one series of land use maps that were sufficiently close to these two dates, however they were not sufficiently detailed and the author provided no details for how they had been produced and thus these were overlooked. Instead, we used remote sensing to produce our own land use maps utilizing satellite images from the United States Geological Survey's (USGS) LANDSAT-1, -5 and -8 satellites. Unfortunately, the first satellite images under the LANDSAT program only became available in 1972, and thus this date was used in place of 1971. As a result, appropriate satellite images from 1972, 1986 and 2014 were downloaded and processed using the method set forth by Andrieu & Mering (2009), relying upon a nested string of k-means classifications (see Table 1 for a more detailed description).

Table 1: Method used to create land use maps for 1972, 1986 and 2014 via remote sensing.

#	Step	Description
1	Download images	Satellite images taken by LANDSAT satellites and covering the study area in 1972, 1986 and 2014 were sourced and downloaded.
2	Fix resolution and extent	The 2014 images were treated to decrease their resolution from 30 meters to 60 meters, for consistency with those of the other dates. The images were then joined and cut so each year had one image that covered the study area.
3	Create false color composite images	Using the GIS and Remote Sensing software IDRISI (now TerrSet), false color composite images were created from the satellite images' raw spectral bands.
4	Split into classes through k-means classification	By means of an unsupervised classification using the k-means algorithm, the pixels were divided into 12 separate classes.
5	Define classes according to radiometric curves	The radiometric curves of the 12 classes were each analyzed and assigned to a category best aligned with their spectral signatures.
6	Consolidate classes to be sufficiently distinct	It was found that, of the 12 classes originally defined, only seven were sufficiently distinct to warrant their own class. The pixels from the extra five classes were reclassified in line with the most appropriate remaining class.
7	Improve classes through stacked classifications	Each of the remaining seven classes was then isolated and had an unsupervised k-means classification performed to split its own pixels into eight separate sub-classes. The radiometric curves were then analyzed and any of these subclasses that were found to belong to another class instead were reclassified to that class. This process was repeated until all classes appeared to be homogeneous.

8	Produce maps of land use and of urban growth	From the resulting seven classes, a land use map was produced for each of the three relevant dates. Additional maps were produced showing Sydney's urban footprint at each of the three dates and how much urban growth had occurred between the dates.
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2.2. Modeling

- 21 After having produced land use maps of Sydney through remote sensing for the years 1972, 1986 and 2014, a model was created to simulate the evolution of the urban development of Sydney. Producing land use maps via remote sensing provided two major benefits to the modeling process. Firstly, the 1972 land use map provided a reliable initial state from which to perform the urban growth simulations. And secondly, the 1986 and 2014 land use maps were taken as credible sources of the actual land use in those years, giving the opportunity to perform an initial calibration of the model. The model took into consideration a number of variables, including the distance to the CBD, Parramatta and the new airport, as well as the proximity to urban land, the proximity to existing roads and the number of land parcels to be urbanized. Simulations were run over the study period and the values of the variables were iteratively varied. The resulting land use maps in 1986 and 2014 were then compared to those produced through remote sensing for the corresponding years. By comparing these maps, it was possible to decide what were appropriate values to assign to each variable in order to produce results that closely resembled the actual urban growth that had occurred. After performing this calibration which assumed a 2014 date of construction for the airport, the model was then used to simulate Sydney's urban growth with the airport being constructed in 1972, 1986 and 2014, varying only the weight of attractiveness assigned to the airport and its date of construction. The UML diagram (Figure 2 below) shows the logical organization and function of the model.
- 22 The model calibration process was separated into two parts: (1) calibrating the rate of urbanization and (2) calibrating the weight assigned to each variable. The rate of urbanization determined how much urban growth occurred each year in the simulations, and the weight assigned to each variable influenced where that urban growth occurred. Calibration of the urban growth rate was done through the use of a simple quantitative analysis. The number of urban land parcels was compared for each of the three remote sensing land use maps produced in order to determine the total area urbanized over the periods 1972–1986 (588 parcels urbanized) and 1986–2014 (420 parcels urbanized). From these figures, the average rates of urbanization used in the model were established for the two date ranges (42 and 15 parcels per year respectively). The model assumed that 42 parcels were urbanized each year from 1973 to 1986, and that 15 parcels were urbanized each year from 1987 to 2014. The weights assigned to each of the variables (excluding that of the distance to the new airport) were calibrated in a series of stages. Initially, the variables were iteratively varied one at a time to determine a reasonable range for each in the first instance. They were then varied in combination with one another within these ranges to establish a select few combinations that appeared to closely resemble the initial state. Finally, these combinations were varied with even more precision until the best combination of variable weights was settled upon. At each stage of this calibration process, visual

analyses were employed to determine which combinations of variable weights best reproduced the actual land use of 1986 and 2014 given by the maps produced through remote sensing. The combination that was chosen yielded results that resembled the actual land use fairly well.

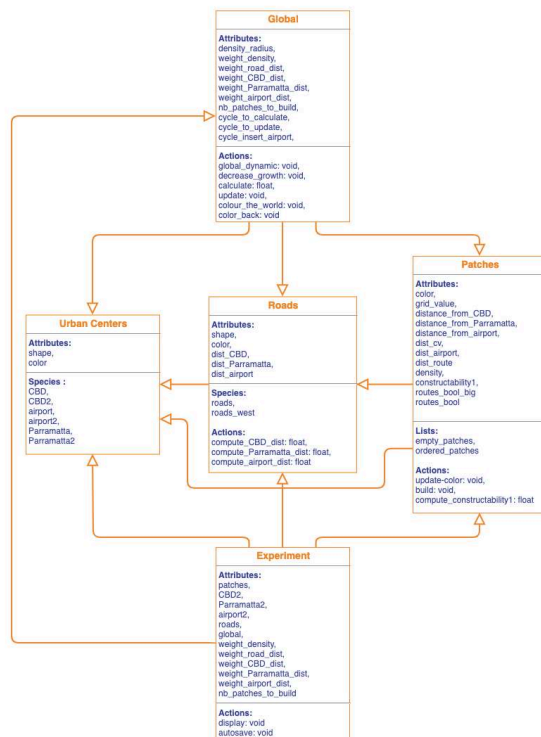
- 23 It is reasonable to expect that, had the new airport been built at an earlier date, Sydney's urban dynamics would have evolved differently to how they have in reality. As a result, the weight each variable exerted on a parcel's constructibility would have likely differed from those chosen in this study. However, given the fact that it is impossible to know how these dynamics would have changed, it seemed prudent to utilize the historical dynamics for all scenarios simulated.

Table 2: Description of variables used by the model to determine the constructibility of each land parcel

Variable	Weight assigned to variable	Description of variable
Distance to CBD	-8	Distance from the CBD via the existing road network.
Distance to Parramatta	-15	Distance from Parramatta via the existing road network.
Proximity to urban land	60	The percentage of parcels within a Chebyshev distance of two possessing an urban land use type.
Proximity to existing roads	5	Euclidean distance from the nearest existing road. Split into three groups to reduce processing time: closest (full score), moderately close (half score) and far (nul score).
Distance to new airport	-x (Different for each simulation)	Distance from the new airport by two means: (1) via the existing road network and (2) Euclidean distance. Euclidean distance was considered in addition to the distance via the road network for this variable since the road network is currently underdeveloped around the airport.

- 24 The mechanism used by the model to decide which land parcels become urbanized in each year of the simulations relied on a parameter called constructibility. At all times, the model kept a running list of all parcels of land in order of constructibility, that is, the likelihood of each one being urbanized during the next year in the simulation. This parameter was calculated for each parcel of land by multiplying the parcel's value for each variable by the weight attributed to each of these variables, then summing the results. For each year of the simulations, the parcels at the top of the list were converted to having an urban land use, then the remaining parcels in the list had their constructibility recalculated for the next iteration.

Figure 2: UML Diagram of the model used in GAMA.



- 25 For all three construction dates, the model was then used to forecast the urban growth to 2034 and 2054. For each scenario simulated, a variety of values were given to the variables in order to analyze the sensitivity of the results to changes from each variable. This also served to determine a reasonable range of results. Apart from the land use maps, there were three other measures that the simulations produced as output: accessibility (the parts of the city that were within 30 minutes of one of the three major urban centers), urban growth in western Sydney and agricultural land loss. More details about the model, such as theoretical foundations, can be found in Section 1.5.

3. Results

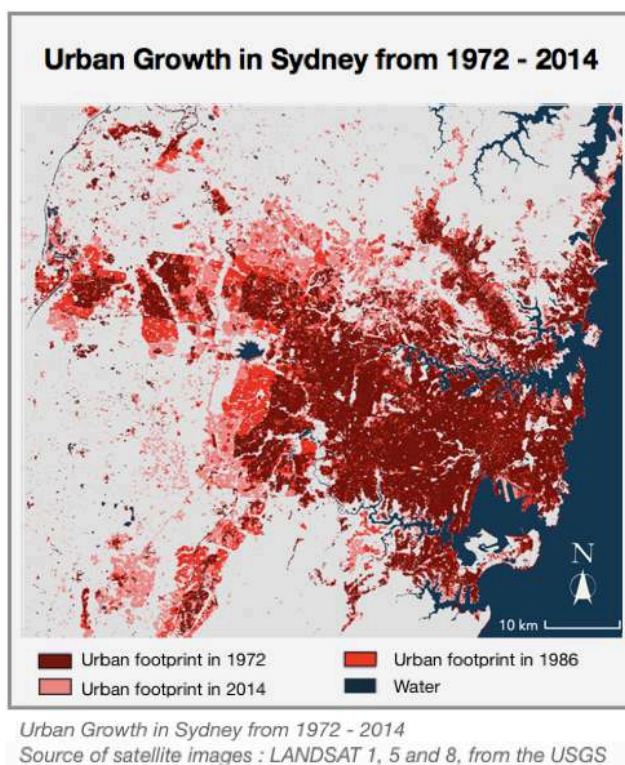
3.1. Land use maps

- 26 The first results of interest are those of the remote sensing undertaken, which take the form of maps reflecting snapshots of the land use in 1972, 1986 and 2014. From these, it is possible to extrapolate some conclusions about the real, existing dynamics of urban growth in the Sydney region over the period between 1972 and 2014. This understanding will help to educate our later analysis of the potential impacts of the delay in the construction of the second international airport in Sydney.
- 27 The maps show the majority of Sydney's growth over the 1972–2014 period occurring in the western parts of the city (Figure 3). This is no surprise, as the territory is bordered on the east by the Pacific Ocean and the north, south and extreme west by National Parks, so the western region now presents the primary opportunity for urban expansion. It can also be seen that the primary regions of urban growth between 1972

and 2014 spread from pre-existing urban areas, illustrating possible and expected path dependence. Areas that were once satellite towns, such as Penrith and Campbelltown became a part of the contiguous urban footprint.

- 28 The maps show also a trend of strong but slowing urban sprawl. According to our analysis, during the 14 years between 1972 and 1986, the surface area of the land with urban land use grew by 44%, while the population grew by only 14%. Thus, Sydney's geographical expansion over this period was in excess of three times as rapid as its population growth. Between 1986 and 2014 - a period twice as long - the urban extent grew by 55%, while the population grew by 38% (ABS, 2014). The rate of population growth had increased, but the comparative rate of sprawl had decreased. The city continued to spread quickly, as urban sprawl still outpaced population growth, but the rate became less extreme.

Figure 3: Results of remote sensing processing for Sydney urban growth from 1972-2014.

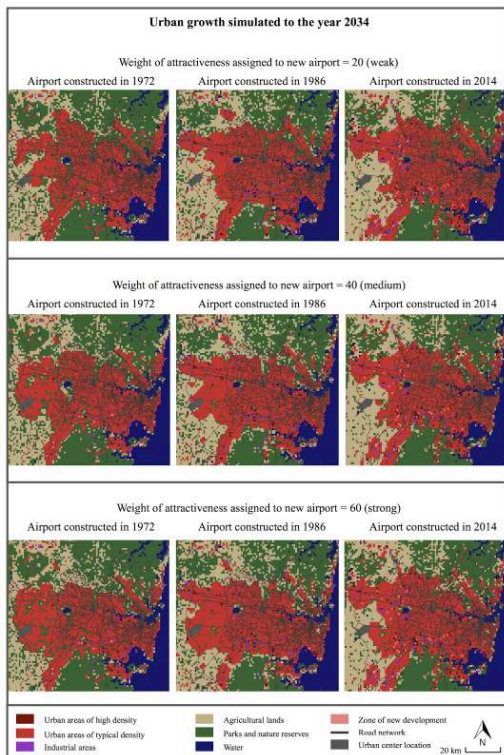


3.2. Modeling

- 29 After calibrating a number of variables to fit the simulations as best as possible to the actual urban development that occurred between 1972–2014 given by the remote sensing, we then performed simulations over the period 1972–2054, varying the level of attractiveness for the airport, as well as its date of construction. Figure 4 below shows a sample of the results for the year 2034, with weak, medium and high weights of attractiveness assigned to the airport (20, 40 and 60 respectively).
- 30 It is worth noting that the three land use maps represent a snapshot in time of Sydney's urban configuration in 1972, 1986 and 2014. Any urban growth that has occurred in reality since those dates has been ignored. Thus, the simulations took into account the

effect each urban center could exert on one another, including the possibility for the new airport to effectively rob the other two urban centers of growth that occurred in reality.

Figure 4: Urban sprawl simulated for year 2034, with the second airport weight at 20 (weak), 40 (medium) and 60 (high).

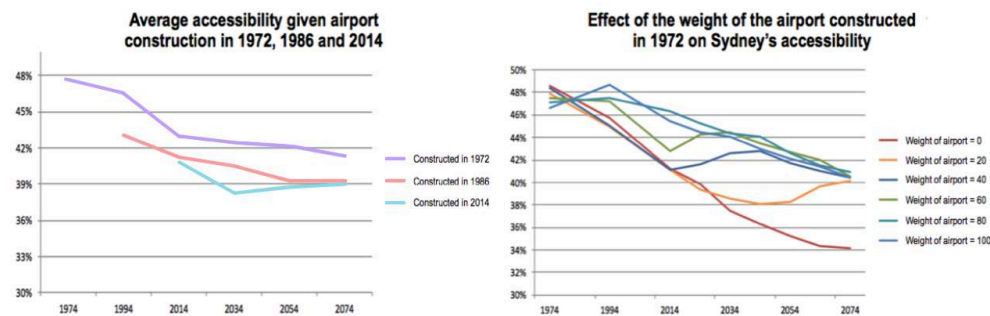


The extreme values simulated (close to 0 and 100) were considered less relevant.

- 31 The modeling of Sydney's urban dynamics revealed a few key trends, as seen in Figure 4. According to the results of these simulations, the weight of attractiveness allocated to the airport was positively correlated with urban growth in the west of the city. Additionally, increased urban growth in Western Sydney was observed to be linked to an earlier date of construction for the airport.
- 32 Another layer of analysis (see Figure 5) found that an earlier airport construction date and a greater weight of attractiveness given to the airport were also positively correlated with the average city-wide accessibility index (one of the key indicators used in this study). Thus, greater levels of urbanization in the west led to superior accessibility on average across the city (n.b. the definition for accessibility was taken as the proportion of urbanized land within a 30-minute travel radius from at least one of the city's three defined urban centers). In fact, when observing the average accessibility across the entire study period for each date of the airport's construction, it was seen to drop from 43.86% in 1972 to 40.67% in 1986 and finally to 39.22% in 2014.
- 33 A noteworthy trend observed was that, regardless of the airport's attractiveness or date of construction, the accessibility index for the city as a whole was in decline over the course of the study period. This leads to the conclusion that the actual sprawl the city experienced had a more significant impact on the city's declining accessibility levels than where the sprawl occurred. The simulations show that, although the decline in

accessibility was somewhat mitigated by airport-related factors, the sheer pace of sprawl built into the simulations was enough to cause unavoidable diminishing city-wide average accessibility. This rate of urban sprawl used in all of the simulations was taken from the real rate of sprawl between 1972, 1986 and 2014 determined by an analysis of the three remote sensing land use maps.

Figure 5: Simulation results for the different scenarios and consequences of the weight of the airport on Sydney's average accessibility.



4. Discussion

4.1. Urban sprawl and densification

- 34 Our approach was oriented around the impact of the airport and its construction date on the configuration of Sydney's urban development. Although our focus was on the location of Sydney's urban sprawl, one of our significant findings was around the rate of Sydney's urban sprawl. Namely, that it has a more notable impact on the city-wide accessibility than any reorienting force the airport is likely to exert.
- 35 In the absence of other forecasts, the rate of sprawl used in the simulations was determined by an analysis of the remote sensing land use maps. The average urban growth between 1972 and 1986 in reality, found by comparing the land use maps for these years, was taken as the rate of sprawl between those dates in the simulations. Subsequently, the average urban growth comparing the land use maps between 1986 and 2014 was taken as the rate of sprawl for the remainder of the study period (i.e. 1986 through 2074). Since urban sprawl was occurring at a greater rate than population growth during these periods, it follows that the population density was decreasing and distances traveled by residents would be increasing. Extending this trajectory beyond the 2014 mark in our simulations only served to exacerbate this effect. As a result, regardless of the location of the new urban development, the simple fact that the simulations all foresaw sprawl outpacing population growth throughout the entire study period was enough to cause the accessibility index to decrease in all scenarios.
- 36 Accessibility is only one issue associated with urban sprawl continuing at the elevated historical rates, however it is the only one simulated by our model. Many other societal problems have been associated with urban sprawl, such as increased traffic and commute times, air pollution, car dependence and a myriad of public health and environmental issues. Despite this, sprawl has historically been a complex issue in Australia where it appears to have been deeply ingrained in the Australian psyche. The prevailing lifestyle is facilitated by urban sprawl and the idea of medium- or high-

density living threatens this existing paradigm. However, the paradigm is beginning to shift. Federal and state governments have recently begun to adopt policies placing a higher emphasis on medium-density housing and encouraging densification. The Low Rise Housing Diversity Code (NSW Government, 2020) is one example. This policy expedites the approval and build processes for medium-density dwellings such as dual occupancy, manor houses and terraces.

- 37 As the federal and state governments over Sydney incentivize medium-density housing and incorporate similar structures into their urban and metropolitan planning, it is likely that Sydney's sprawl will slow. Thus the rate of sprawl used in the simulations would be an overestimate of the actual urban growth experienced by the city. The area around the new airport is likely to still experience significant urban expansion, however, as all levels of government are incentivizing development here.
- 38 Considering the fact that an airport brings a degree of urban sprawl and diffusion within its vicinity (Freestone, 2009), we believe it is necessary to put in place a strategy to mitigate these effects. As airport-related dynamics are not necessarily guaranteed, urban planning regarding density and diversity might constitute a base for more sustainable urban development from a broader perspective. As mentioned by Robert Freestone (2009) in the case of the United Kingdom, sustainable aviation is aided by the inclusion of local communities, which allows for a link between the large and the small scale.

4.2. Social implications

- 39 The results of this study consist of timing and spatial measures related to the urban form of Sydney. They define how the urban structure and configuration of the city may have been different if the second international airport in Sydney had been constructed in 1972 or 1986 as opposed to 2014. Beyond these, it is also important to consider the social implications, given the inter-relatedness of spatial and social aspects. It is important to note, however, that urban development is being used as the primary determiner for the discussion of these social issues, although it is not a perfect predictor of these effects. As the simulation does not include social parameters, this study makes general interpretations regarding the expected consequences of the urban sprawl observed with relative prudence. Further discussion in relation to environment protection or social consequences is considered with greater caution.
- 40 One first major social implication considered is the potential impact of the new airport on the well-documented inequalities that exist between the east and the west of the city. These inequalities are due to the fact that Sydney is very CBD-centric (Terrill *et al.*, 2017; Humi, 2005), which is characterized by a saturation of employment opportunities, economic impact and traffic flows into the CBD. The latter has been the subject of much analysis. One hypothesis could be that the increased development in Sydney's west observed with the airport being constructed in 1972 and 1986 in this study's simulations suggests that an earlier construction date for the airport could have potentially provided an opportunity for the redistribution of wealth, accessibility and opportunity between the city's eastern and western residents. But in order for this to be the case, the airport's presence would need to be proven to be the explanation for the economic growth and wealth redistribution that occurred over this time period. Sydney is relatively mono-centric when it comes to employment, economic impact and

transport flows, with the CBD being its major urban center. This configuration has led to traffic congestion and increasing commute times. One issue that is more likely to have been improved if the airport had been constructed earlier is commute times. Deloitte performed a study in 2018 which found that the average commute time to or from Sydney's CBD was 63 minutes each way. This far exceeds Sydney's average commute time of 35 minutes per leg. This congestion has likely been exacerbated by residents of Western Sydney commuting long distances into the CBD, especially given that Sydney's 2016 census showed that almost half (roughly 47.8%) of the city's population resides in the Greater Western Sydney area (ABS, 2017). If the new airport in Badgerys Creek is supported by appropriate policy and commercial interest, it is feasible that an abundance of jobs and transport infrastructure could be introduced to the surrounding areas. This in turn could potentially serve to ease Sydney's reliance on its CBD and help move the needle towards greater equality between the residents in the city's east and west, to curtail the elevated commute times.

4.3. Environmental factors

- 41 As previously mentioned, since the focus of our study is centered around urban development, we tread with caution when making social or environmental observations as our study was not designed to give insight into these aspects. However, it would be imprudent to discuss the role of an airport without looking into, at least partially, environmental factors, given their importance within the debate surrounding airports and the aviation industry as a whole. Consequently, we will briefly touch on these issues, however we will leave in-depth discussion for future studies which orient themselves more directly around these questions.
- 42 To begin, we consider the significant issue of greenhouse gas emissions. The second social implication considered, commute times, is inextricably linked with the resulting greenhouse gas emissions produced. A reduction in commute times and distances, if that was to indeed happen with the construction of the new airport, would lead to a reduction in greenhouse gas emissions resulting from those traffic flows. The extent to which this may have occurred with any of the three relevant airport construction dates is uncertain and would be difficult to estimate. On the other end of the spectrum, the second Sydney airport could increase greenhouse gas emissions through facilitating greater access to air transport. The construction of the second Sydney airport starting in 2014 was (prior to the COVID-19 pandemic) projected to service 82 million passengers annually by 2063 (Commonwealth of Australia, 2016). Since demand seems to be the driver for this additional air travel, it is likely that the number of flights from Sydney would not have been impacted too severely by a different construction date for the airport. Loader (2019) found that, given the typically high occupancy of flights to and from Sydney and the typically low occupancy of travel by car, the average greenhouse gas emissions per passenger per kilometer in Sydney has actually been slightly higher for travel by car than by plane since roughly 1998. Prior to this time, air travel involved more emissions per passenger per kilometer than car travel. Despite this, the emissions associated with the increase in flights to service an additional 82 million passengers would be likely to exceed any savings associated with the expected reduction in commute times. This is a key consideration in the decision to construct any airport.

- 43 Another environmental implication of the second international airport in Sydney is that of noise, air and water pollution. Given that the airport construction project is a greenfield development and is quite isolated from existing urbanized land, our focus is placed on the environmental impacts of these factors as opposed to the impact on people. noise pollution is unlikely to be an issue for existing residents or businesses. This is likely a key reason why the airport has been given permission to operate without a curfew, unlike the existing airport closer to the CBD. Air and water pollution, however, are more pertinent to this discussion. It has been suggested that the flight paths of the planes landing at and taking off from the Western Sydney Airport could bring unacceptable levels of pollution to two major sites. The first site in question is the Warragamba Dam, which is Sydney's main drinking water source. The Environmental Impact Statement acknowledged the risks, however it found that the inherent risk to the drinking water associated with the airport's operations was low, being further reduced by mitigation plans that were set in place. The second site is the Greater Blue Mountains World Heritage Area; an area that has been listed as a UNESCO World Heritage site since 2000. The plans to build an airport in the Badgerys Creek location were included in the World Heritage submission and the site was registered on the World Heritage list with this in mind. One of the assessing bodies, the International Union for Conservation of Nature (IUCN), found that the Environmental Impact Statement was comprehensive and they noted that the airport would have no adverse effect on the area's ecological processes (IUCN, 2000). The date of construction of the airport is unlikely to have had a major impact on these issues, since both sites have occupied the same areas since the beginning of the study period. The one potential exception is that the Environmental Impact Assessment was likely completed with additional rigor and detail in the 2014 scenario due to the Blue Mountains site being inscribed in the UNESCO World Heritage List.
- 44 The final environmental consideration we will cover is the loss of agricultural land to make way for the greenfield airport in Badgerys Creek and any urban development in the same area. As the Greater Sydney region is surrounded by ocean to the east and protected National Parks to the north, south and far west, the remaining areas that have the potential to be urbanized are agricultural land in the near west. The land around the airport site fits that description, so any new developments in support of the new airport are likely to contribute to a loss of agricultural land. The draft Aerotropolis Precinct Plan (2020) that is most current at the time of writing does designate certain areas near the new airport for agricultural land, however it also sets apart substantial portions of existing agricultural land to be urbanized. This could further increase Sydney's reliance on imported fresh food, reducing the city's resilience. It is reasonable to assume that an earlier construction date for the airport would have accelerated the loss of agricultural land in the first instance, however it is difficult to know whether there would be any perceptible difference between scenarios if we were to project into the future.

4.4. Limitations of study

- 45 One element that characterizes this study is its distinctive handling of timing. Instead of simply considering actions that could be taken now to impact the future, we considered actions that could have been taken in the past and simulated their impact on both the present and the future. That is, we considered how the present and future

urban form of Sydney could have been impacted by the second international airport in Sydney being constructed at an earlier date. Although this consideration of timing is a distinctive feature of this study, it is also the source of one of its limitations. Chaos theory suggests that it is possible for a small change in initial conditions to have an immense and unpredictable impact on the future. In this case, an earlier date of construction for the airport could have potentially had an immense and unpredictable impact on Sydney's current and future urban form. While historical data was used to calibrate the simulations in order to bring a degree of rigor to the results, it is impossible to anticipate if the reality would have conformed with our expectations.

- 46 The model itself was also aimed at clarifying only the general expected trends related to Sydney's urban area and the distribution of accessibility within. As a result, certain more complex factors impacting urban development that are found in the relevant academic literature were omitted. This includes elements such as social, economic and political factors, as well as the topography of the land and certain types of urban expansion such as leapfrog development. Consequently, while the simplicity of the approach lends itself to identifying clear global trends, the dynamics observed at a granular level will have limited significance.
- 47 A significant limitation that is of increased relevance since the modeling was performed is that the simulations do not take rare or unexpected events into account. The COVID-19 pandemic, beginning in early 2020, is an external variable that has had an extremely disruptive effect on air travel and airport systems. It is likely that the interplay between airports and the surrounding urban development will change in the wake of this pandemic, however it is difficult to predict in what ways. On one hand we could make the optimistic hypothesis that because it is a crisis on both demand and supply, the airport systems could recover to a state that resembles the one prior to the crisis. However the extent of the disruption to the air travel industry caused by this pandemic is likely to trigger some significant changes to the industry itself and the connectedness of the world. How this will impact the previously burgeoning importance of an airport within a city's urban system, it is too early to tell. Due to the many elements that currently remain unknown, we prefer to keep our interpretation to the limits of what can be observed from the modeling that was performed before the crisis began. It would be possible for future works to incorporate other variables to better reflect a situation similar to this one, however since our study was an attempt to clarify the spatial relationships between airport planning and urban sprawl, this is an added element of complexity that was not factored in.

4.5. Airport timing and accessibility

- 48 In the results section, it was demonstrated that the new airport impacted the city's accessibility level throughout each of the scenarios simulated. In each case, it could be seen that the overall city-wide accessibility index was superior given an earlier construction date for the airport and a higher weight of attractiveness applied to the airport. The applicability of this general trend to reality is predicted on a few interrelated factors.
- 49 First, it seems impossible to determine precisely how much of an attractive force a new airport or other feature of a city will exert. This is complex and is undergirded by multiple elements and influenced by a variety of stakeholders. Some factors

contributing to the attractiveness of the second Sydney airport are the commercial management of the airport and its operations, competition with Kingsford Smith Airport, negotiations with airlines, Sydney residents' demand for air travel, international travelers' appetite for travel to Sydney and their choice of airlines, public policy surrounding transport, infrastructure and urban planning, securing of anchoring tenants for the Aerotropolis business parks, macroeconomic trends and airline industry developments to name a few. Airport and government stakeholders have significant parts to play in creating an environment that amplifies the airport's attractiveness, however they do not hold all the cards.

- 50 It is also interesting to note that the attractiveness of the airport is likely to have been negatively correlated with an earlier construction date for the airport. In 1972, and to a lesser extent 1986, the airport site in Badgerys Creek was far more isolated from the urban extent of Sydney, leading to a far smaller proportion of the population likely to gravitate towards using it. The demand for air travel at the time was also significantly lower and the existing airport better equipped to cope with the existing demand. In the event of a two airport system where there is only enough demand for one to absorb it all, the ensuing success of the newer airport is quite uncertain. Thus, it is quite plausible that the second airport would not have become a commercial success if it had been built at one of the earlier dates, as De Neufville (1991) suggested. If this were to be the case, it is uncertain whether the airport would be a delayed success as with Washington Dulles which was underutilized for two decades, or whether it would become a white elephant, as with Montreal Mirabel, which never recovered (Chambers, 2005).
- 51 Since our model simulates a variety of scenarios with the airport being given varying levels of attractiveness, it is difficult to determine which is the most likely to have occurred. The range of possibilities is wide and there is more in common between the different dates of the airport's construction than there is separating them. However, broadly speaking, we can outline the main points of difference between the three alternate outcomes as follows. In the case of 1972, there is the potential for the greatest level of urbanization in the west of Sydney and the highest resulting accessibility. However, there is also the greatest risk that the airport would not be a commercial success. As a result, this scenario brings with it the highest likelihood that the airport would exert little to no attractive force and thus have little to no impact on the urban development of the city. In essence, the 1972 case has the greatest potential upside while also having the highest risk of being ineffective. On the other end of the spectrum, the 2014 case seems to provide the most favorable conditions for the airport to succeed and exert an influence on the city's urban configuration, however the delay has dampened the potential intensity of its influence. This appears to be the lowest risk, lowest reward scenario. The 1986 case provides a middle ground, where the resulting accessibility is likely to be moderate, while the risk of it being inadequately attractive to influence Sydney's urban development is elevated, though to a lesser extent than the 1972 case.

5. Conclusion

- 52 This study attempted to undertake an analysis of the impact on the urban development of Sydney caused by the deferral of the construction of its second international airport

from 1972 and 1986 to 2014. In the absence of existing data, remote sensing was completed for the relevant dates and this was used as the basis for the study of Sydney's accessibility and urban form. A model was also created to simulate the city's urban development between and beyond these dates.

- 53 The land use snapshots for the three relevant years, produced using remote sensing, show that the actual urban growth dynamics evolved over this period. The rate of urban growth was elevated in the period from 1972 to 1986 when compared with the period between 1986 and 2014. Using CA modeling, simulations were performed for Sydney's urban development given construction dates for the airport of 1972, 1986 and 2014. These simulations taken in isolation revealed three key trends, all else being equal. (1) The urbanization of the western part of the city is likely to have been higher if the airport had been constructed in 1972 than at the later dates. (2) The city's accessibility index is likely to have been higher if the airport had been constructed in 1972 than at the later dates. (3) The greater the weight of attractiveness exerted by the airport, the more urbanization occurred in the west of the city and the higher the accessibility index.
- 54 The first two trends seem to point to the 1972 scenario leading to a more poly-centric and accessible city. To grasp the implications of the third trend, however, requires the consideration of factors that are external to the simulations. It is likely that the attractiveness of the airport would have been stronger in scenarios with later construction dates, due to, among other things, commercial considerations, thus producing the opposite effect to the first two trends – a more poly-centric and accessible city in the 2014 scenario. In reality, the conflicting effects of these trends produces a set of potential outcomes that could have occurred in the given scenarios. The 1972 scenario brings the greatest potential for development in Western Sydney and increased city-wide accessibility, but the greatest risk of no effect. The 2014 scenario, however, presents the least potential for development in Western Sydney and increased city-wide accessibility, but the lowest risk of no effect. The 1986 scenario represents the middle ground – moderate potential with moderate risk. Given the hypothetical nature of the scenarios simulated, it is impossible to be certain of what would have happened, however this outline provides insight into some potential effects of the airport's deferral.
- 55 The results of this study confirm that it is crucial to consider timing when planning the construction of a new major airport. Every major airport leaves a permanent mark on the spatial configuration of its city, and its date of construction can shape this mark. Thus, timing is a key factor that can improve the likelihood that the airport will contribute to the urban development of the city in a way that is desired. We believe that the approach used in this study could be applied for various infrastructure projects and has the potential to enlighten planning debates beyond the case of a second airport.

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ABSTRACTS

Airports serve as more than simply ports of entry and exit for air travel. They have a significant impact on the configuration and functions of the cities they serve. As such, the timing of their construction is a key factor for cities to consider. The second Sydney airport is currently under construction in the west of the city at Badgerys Creek. This project was previously considered on two occasions: in 1971 and 1986. Primarily through modeling, this study explores the impacts on Sydney's urban development, and subsequently other aspects of the city, that could have resulted if the airport had been built on one of these dates instead of 2014. The results indicate that the earliest date of construction for the airport presents the greatest potential for inducing urban development in its vicinity and improving accessibility, but also the greatest risk of being ineffective. In turn, the latest date provides the least potential for urban reconfiguration and accessibility gains but the lowest risk of being ineffective. It is clear that timing is an important factor to consider when planning the construction of an airport, however it should be considered in conjunction with the broader picture.

Les aéroports ne fonctionnent pas seulement comme des points d'entrée et de sortie pour le transport aérien. Ils ont un impact significatif sur la configuration et le fonctionnement des villes qu'ils desservent. Il est donc impératif de bien choisir le moment de leur construction. Le deuxième aéroport de Sydney est actuellement en cours de construction à l'ouest de la ville à Badgerys Creek. Ce projet a déjà été considéré à deux dates précédentes : en 1971 et en 1986. À partir d'une modélisation à base d'agents, cette étude examine les impacts du report à 2014 de cette construction sur le développement urbain de Sydney. Les trois dates sont donc simulées à cet effet. Les résultats de la simulation montrent que la construction de l'aéroport à une date antérieure aurait eu la probabilité la plus élevée de rediriger la croissance urbaine aux alentours et d'améliorer l'accessibilité de la ville, mais elle aurait aussi eu le risque le plus élevé d'être inefficace. Réciproquement, la construction de l'aéroport à une date ultérieure aurait eu la probabilité la plus faible de rediriger la croissance urbaine aux alentours et d'améliorer l'accessibilité de la ville, mais elle aurait aussi eu le risque le plus faible d'être inefficace. Il est clair que le timing est un élément important à prendre en compte lors de la planification de la construction d'un aéroport, même s'il doit faire partie d'une considération plus globale.

Los aeropuertos funcionan más allá que lugares de entrada y salida de transporte aéreo. Estos presentan un significativo impacto en la configuración y funcionamiento de las ciudades en que están localizados. Por lo tanto, resulta fundamental tomar decisiones pertinentes al momento de su construcción. El segundo aeropuerto de Sídney está actualmente en construcción al oeste de la ciudad en Badgerys Creek. La puesta en marcha de este proyecto fue considerada en dos fechas con anterioridad: 1971 y 1986. Así, por medio de una modelización, este estudio examina los teóricos impactos en el desarrollo urbano de Sídney, y en otros aspectos de la ciudad, si el aeropuerto hubiese sido construido en alguna de esas fechas en vez del 2014. Los resultados indican que la fecha más temprana de construcción presenta las probabilidades más altas para inducir un desarrollo urbano en las proximidades y mejorar la accesibilidad, pero también ostenta un mayor riesgo de ineficacia. Respecto a la fecha más reciente, revela una menor potencialidad en tal reconfiguración urbana, el mejoramiento de la accesibilidad y con un riesgo

menor de ser ineficaz. Se concluye que el tiempo es un importante factor a considerar cuando se planifica la construcción de un aeropuerto, la cual debería abordarse en su globalidad.

INDEX

Palabras claves: desarrollo urbano, modelización, simulación, autómatas celulares, teledetección, planificación urbana

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