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Remote work: Aircraft noise implications, prediction, and management in the built environment

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Abstract

The COVID-19 pandemic has greatly changed workplace management. Most workplaces have adopted the work-from-home policy to minimize the risk of community spread. Consequently, housing estates remain largely occupied during office hours. Since some housing estates are situated in the vicinity of an airport, noise pollution resulted from the takeoff and landing of aircraft is now more noticed by residents, causing annoyance. This problem would be most acute for those located directly under the flight path. Before the pandemic, such aircraft operations had lower effect on the residents because most of them were not at home but at workplaces. Evidently, it is timely that more emphasis should now be placed during urban planning to predict and minimize aircraft noise in the built environment. This article first defines the aircraft noise metrics commonly used to assess environmental impact. Preceded by an overview of how aircraft noise affects the built environment, this article reviews how various aircraft noise prediction models have been used in urban planning. Lastly, this article reviews how aircraft noise can be managed for better acoustic comfort of the residents. Anticipating the adoption of hybrid work arrangement moving forward, this article aims to provide urban planning professionals with an avenue to understand how aircraft noise can negatively affect the built environment, which, in turn, justify why prediction and management of aircraft noise should be emphasized from the outset of urban planning.

Keywords:
Aircraft noise
Urban planning
Noise mapping
Remote work
Environmental noise

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Abbreviations: AEDT, Aviation Environmental Design Tool; ANC, Active Noise Control; ANP, Aircraft Noise and Performance; BADA, Base of Aircraft Data; CAA, Civil Aviation Authority; CNEL, Community Noise Equivalent Level; DLR, German Aerospace Center; ECAC, European Civil Aviation Conference; FAA, Federal Aviation Administration; ICAO, International Civil Aviation Organization; INM, Integrated Noise Model; NASA, National Aeronautics and Space Administration; NDI, Noise Depreciation Index; SEL, Sound Exposure Level; WECPNL, Weighted Equivalent Continuous Perceived Noise Level; WHO, World Health Organization; $L_{Aeq}$, $L_{Aeq}$, $L_{day}$, $L_{dn}$, $L_{max}$, Maximum A-Weighted Noise Level, $L_{eq}$, Day-Evening-Night Noise Level, $L_{dn}$, Day-Night Noise Level.

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https://doi.org/10.1016/j.apacoust.2022.108978
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1. Introduction

In many countries, the COVID-19 pandemic has greatly changed workplace management. This disruption has put forth the most rapid workplace transformation. To promote social distancing and minimize the risk of community spread, workplaces are forced to rethink how work is being done and adopt the work-from-home arrangement within a short period of time. Consequently, residential buildings remain largely occupied during office hours.

Since many individuals have been working from home and meeting virtually, road traffic has significantly dropped. In Asia, recent studies [1–3] consistently reported that the work-from-home arrangement due to the COVID-19 pandemic has helped to reduce traffic noise pollution especially during peak hours. For housing estates in the vicinity of an industrial zone, the residents have benefited the most from the reduced noise exposure. In Europe and North America, there are consistent evidence [4–8] as well reporting the positive effect of work-from-home arrangement on traffic noise pollution. However, Terry et al. [8] found that residents staying near to the expressway may not enjoy the full benefit of a quieter environment because of the noise produced by vehicles traveling at high speed.

Owing to domestic and international travel restrictions amid COVID-19 pandemic, air traffic has decreased as well. In some airports, business and personal trips are prohibited temporarily. This prohibition provides researchers with the opportunity to study the contribution of air traffic toward noise pollution, which would not have been possible pre-COVID-19 pandemic. In a noise monitoring study conducted over nearly two months at Athens International Airport and along the Attica Tollway, Vogiatzis et al. [7] discovered that the drop in day-evening-night noise level (L den) caused by the decrease in air traffic was 2–3 dB(A) more compared to that caused by the decrease in road traffic. In Paris, Aletta and Osborn [9] reported that the drop in road traffic led to a noise reduction of 7.6 dB(A) (L den), while the prohibition of air traffic at Paris Charles de Gaulle Airport resulted in an astounding noise reduction of 21.5 dB(A) (L den). These reports are consistent in suggesting that reduced aircraft operations can significantly affect noise pollution.

In most airports, cargo flights are still permitted to facilitate the transportation of goods, commodities, and medical supplies. In a recent report published by the International Finance Corporation [10], they found that the volume of cargo flights has increased due to the rapid growth in demand for e-commerce. To meet this growing demand, passenger aircraft are repurposed for cargo by some airlines. This finding provides the understanding that residents staying near to or under the flight path of cargo aircraft are likely to experience the same, if not more, amount of noise pollution despite having domestic and international travel restrictions in force. Indeed, in an article published in The New York Times, Zipkin [11] reported an alarming surge in noise complaints filed by residents from various states of Canada and the United States due to the increased air traffic of cargo flights. The number of complaints was comparable to that received by the US Congress 30 years ago when aircraft were inefficient.

Apart from cargo flights, the volume of sightseeing flights has also increased. In an article published in the Montreal Gazette, Gyulai [12] interviewed the residents of Montreal, Canada, and revealed how they were disturbed by the spike in low-flying sightseeing flights while working from home. Owing to travel restrictions, the number of sightseeing flights spiked because of residents who resorted to local tourism. Some residents even made use of this period to acquire private pilot licenses, which contributed to increased noise pollution. The noise pollution would worsen when low-flying helicopters flew over the housing estates. One interviewee commented that the noise complaints would not have increased if residents were not home in the daytime, which was the case pre-COVID-19 pandemic. Like the issue with cargo flights [11], the number of noise complaints and severity of noise pollution have caught the attention of the Government.

Up to this point, it is clear that domestic and international travel restrictions do not necessarily reduce noise pollution in housing estates. Civil flights that are still permitted continue to emit environmental noise, causing annoyance and disturbance to the residents. Owing to work-from-home arrangement, residents are home in the daytime to realize the unwanted noise, leading to the surge in noise complaints. Even if this issue was present pre-COVID-19 pandemic, most residents would unlikely be home to realize it and cause the surge in noise complaints.

Civil flights, however, are not the sole contributor to aircraft noise in housing estates. Military flights play a part as well and are generally louder than civil flights due to the use of low-bypass turbojet engines. Residents who reside in the vicinity of an airbase are most affected when fighter jets takeoff and land. During takeoff, afterburners are used to greatly increase thrust, allowing the fighter jet to become airborne with minimum ground roll. This procedure causes the exhaust air to be at supersonic speed, creating shock waves that produce loud noise. During landing, thrust reversal is activated shortly after touchdown to rapidly decelerate the fighter jet down to the taxi speed or a complete stop.
This procedure generates loud noise due to the interaction of highly turbulent air between the engines and the fuselage. In an article published in the Honolulu Civil Beat, Knodell [13] reported that residents in Oahu, Hawaii, became more aware of military flights after having to stay home in the daytime due to COVID-19 restrictions. Concurrently, the noise pollution worsened with the increase in operations and pilot training due to political reasons. As such, formation flights could take place as frequent as every hour. Similarly, in a CNA commentary, Yeo [14] shared that military flights have affected work-from-home residents in Singapore during the daytime. Owing to land scarcity, the noise pollution could easily affect residents of various towns that are in close proximity to the airbase. For example, the residents of Punggol and Sengkang towns would be acutely disturbed whenever fighter jets took off from the nearby airbase because the two towns are located directly under the flight path. Owing to high volume of noise complaints, the Government took measures to minimize noise pollution by shifting pilot training overseas and limiting flight events at night and during sensitive periods. In another article published in the WECT News, Praats [15] reported that the Wilmington International Airport was repurposed for military use due to domestic and international travel restrictions. Although nearby residents raised concerns about being affected by the jet aircraft noise, the airport management justified that the aim was to help businesses stay afloat and retain employees.

When the COVID-19 pandemic becomes endemic, employees will be expected to return to work in the office. Even though work may no longer be done entirely from home in the near future, recent surveys [16,17] indicated that workplaces may adopt hybrid work arrangement in which employees will only be required to be physically present in the office on certain days. To date, aircraft noise remains a pressing issue in the built environment due to low emphasis during urban planning pre-COVID-19 pandemic [18]. Since the literature has revealed how residents are becoming more aware of aircraft noise and are being affected by it while working from home in the daytime, it is timely to now emphasize the need for aircraft noise prediction during urban planning. In this way, feasible noise control measures can be considered in the design of housing estates from the outset so that less noise complaints are expected from new residents.

Following this introduction, Section 2 defines the aircraft noise metrics commonly used to assess environmental impact. Section 3 overviews how aircraft noise can affect the built environment in two key areas—public health and property value. Section 4 presents the various aircraft noise prediction models and how they have been used in urban planning by reviewing case studies reported over the last decade. This 10-year coverage (2011–2021) helps to limit the scope and ensure recency. Section 5 reviews the management of aircraft noise via the Balanced Approach and the state-of-the-art (5-year coverage) in aircraft noise control measures that could potentially be incorporated in housing estates for better acoustic comfort. Lastly, a conclusion is provided in Section 6. In essence, this review article aims to provide urban planning professionals with an avenue to understand how aircraft noise can negatively affect the built environment, which, in turn, justify why prediction and management of aircraft noise should be emphasized from the outset of urban planning, anticipating how hybrid work arrangement may be adopted amid COVID-19 endemic.

2. Aircraft Noise Metrics

As a prelude to the subsequent sections, it may be beneficial to first understand how aircraft noise is being quantified in the context of environmental impact. Owing to decades of research, many noise metrics (or noise descriptors) have been developed to quantify aircraft noise for the assessment of its severeness [19]. Among the various noise metrics, some are commonly used and accepted internationally [20]. This section is limited to the definition of the commonly used noise metrics which can essentially be categorized into two types—single event (Section 2.1) and cumulative (Section 2.2).

![Fig. 1. Schematic diagram of the typical level-time history of a single flight event in which the aircraft approaches and leaves a given observer location. \( L_{AE} \) denotes the A-weighted sound exposure level (SEL); \( t_1 \) and \( t_2 \) denote the time period for SEL computation; and \( L_{A_{\text{max}}} \) denotes the maximum A-weighted noise level.](image-url)
2.1. Single Event Noise Metrics

This type of noise metrics describes the noise level of a single flight event at a given observer location. The commonly used noise metrics are the maximum A-weighted noise level ($L_{\text{Amax}}$) and the A-weighted sound exposure level ($L_{\text{AE}}$) [20]. These metrics describe the noise level in A-weighting, which is widely accepted by international standards as the approach to consider the sensitivity of human ears to the audio frequency range (20 Hz to 20 kHz).

2.1.1. Maximum Noise Level

The maximum noise level can be better explained by the level-time history of a single flight event at a given observer location (Fig. 1). As the aircraft approaches the observer location, the distance between both entities decreases with time, leading to the increase in noise level up to a maximum point ($L_{\text{Amax}}$). As the aircraft flies past the observer location, the distance between both entities increases with time, leading to the decrease in noise level. It is important to note that depending on the aircraft, the maximum noise level may not necessarily occur at the minimum distance between the aircraft and the observer location. Mathematically, the $L_{\text{Amax}}$ noise metric is expressed by

$$L_{\text{Amax}} = \max[L_a(t)]$$

where $L_a(t)$ denotes the instantaneous A-weighted noise level at a given time $t$.

Although the $L_{\text{Amax}}$ noise metric is useful to indicate the maximum noise level of every flight event, it does not account for the duration of the event. For two independent events, the maximum noise level can be identical, but the duration in which how long each event lasted is unknown. Hence, the observer may experience an entirely different noise exposure in both events.

2.1.2. Sound Exposure Level

Unlike the $L_{\text{Amax}}$ noise metric, the $L_{\text{AE}}$ noise metric considers the time component. The duration of the flight event is defined by the time period when the noise level is 10 dB below the maximum noise level ($L_{\text{Amax}}$) (between $t_1$ and $t_2$) in Fig. 1. In this time period, the total amount of acoustic energy is normalized to a time period of 1 s, leading to the sound exposure level of the event. Mathematically, the $L_{\text{AE}}$ noise metric is expressed by [20]

$$L_{\text{AE}} = 10\log_{10}\left[\int_{t_1}^{t_2} 10^{L_a(t)/10} \text{d}t\right]$$

where $L_a(t)$ denotes the instantaneous A-weighted noise level at a given time $t$; $t_1$ and $t_2$ denote the time period when the noise level is 10 dB below the maximum noise level; and $t_1$ is equal to 1 s.

Since the duration of every flight event is normalized to 1 s, the $L_{\text{AE}}$ noise metric is useful to fairly compare the noise exposure experienced by the observer across different events. For two independent events with identical maximum noise level but different duration, the more concerning event is the one with higher $L_{\text{AE}}$ value. Due to this characteristic, the $L_{\text{Amax}}$ noise metric is generally preferred over the $L_{\text{AE}}$ noise metric because it is difficult to fully comprehend the concept of the latter, especially by non-specialists. Owing to the normalization, the $L_{\text{AE}}$ value is expected to be higher than the $L_{\text{Amax}}$ value by about 10 dB for most events [20].

2.2. Cumulative Noise Metrics

This type of noise metrics describes the noise level at a given observer location over a period of time—daily, monthly, or annually, for example. Unlike single event noise metrics, cumulative noise metrics can include more than one flight event. Commonly used noise metrics include the weighted equivalent continuous perceived noise level (WECPNL), the day-evening-night noise level ($L_{\text{DEN}}$), and the day-night noise level ($L_{\text{DN}}$) [19]. As discussed in Section 2.1, the A-weighting is adopted to describe the respective noise levels.

2.2.1. Weighted Equivalent Continuous Perceived Noise Level

The WECPNL noise metric originates from the International Civil Aviation Organization (ICAO) [21] and has been commonly adopted in China, Japan, and South Korea with slight modifications for simplicity [22]. Mathematically, the WECPNL noise metric, in its simplified form, is expressed by [23]

$$\text{WECPNL} = \frac{L_{\text{Amax}}}{10} + 10\log_{10}(N_d + 3N_e + 10N_n) - 27$$

where $L_{\text{Amax}}$ denotes the average maximum A-weighted noise level of all flight events for the entire day (24-hour period); $N_d$ denotes the number of flight events during the day (7 am to 7 pm); $N_e$ denotes the number of flight events during the evening (7 pm to 10 pm); and $N_n$ denotes the number of flight events during the night (10 pm to 7 am). Sometimes, the night time is divided further into 10 pm to 12 am and 12 am to 7 am for greater emphasis (weighting factor remains identical at 10).

In view of standardization, newer studies in Japan and South Korea have started to transit from the WECPNL noise metric to the $L_{\text{DEN}}$ noise metric. For past data, the relationship between both noise metrics must first be established so that they can be converted into the equivalent $L_{\text{DEN}}$ value for fair comparison with newer data [24]. This area of research has been ongoing [25].

2.2.2. Day-Evening-Night Noise Level

The $L_{\text{DEN}}$ noise metric is computed from the average A-weighted noise level measured over the entire day (24-hour period). As implied by the metric name, the time period is divided into three parts—day (7 am to 7 pm), evening (7 pm to 11 pm), and night (11 pm to 7 am). In the computation, a 5 dBA penalty is added to the evening noise level ($L_{e}$), while a 10 dBA penalty is added to the night noise level ($L_{n}$). These penalties are added to include the heightened sensitivity of humans to noise events in the evening and at night. No penalty is added to the day noise level ($L_{d}$). Mathematically, the $L_{\text{DEN}}$ noise metric is expressed by [26]

$$L_{\text{DEN}} = 10\log_{10}\left[\frac{1}{T} \left(\int_t^{t_2} 10^{L_a(t)/10} \text{d}t + 10^{L_{d}/10} + 10^{L_{e}/5+10} + 10^{L_{n}/10}\right)\right]$$

where $T$ denotes the total time period (i.e., 24 h); $t_2$, $t_{d}$, and $t_{e}$ denote the number of hours during the day, evening, and night, respectively. By default, $t_d$, $t_e$, and $t_n$ are equal to 12, 4, and 8 h, respectively.

In some countries, the $L_{\text{DEN}}$ noise metric is also known as the Community Noise Equivalent Level (CNEL). This noise metric is particularly useful to compare the noisiness between neighborhoods. By considering how noise can affect humans differently over the entire day, the $L_{\text{DEN}}$ noise metric (or CNEL) is regarded as a simple yet appropriate approach to determine long-term aircraft noise exposure contributed by all flight events from the airport of interest [27]. All variations in aircraft performance and flight path are considered. As such, the $L_{\text{DEN}}$ noise metric (or CNEL) is widely used internationally by more than 20 countries [19].

2.2.3. Day-Night Noise Level

The $L_{\text{DN}}$ noise metric is computed in a manner similar to the $L_{\text{DEN}}$ noise metric except that the time period is divided into two parts—day (7 am to 10 pm) and night (10 pm to 7 am). The night noise
level \(L_d\) is still added with a 10 dBA penalty and is regarded as the key indicator for sleep disturbance \[28\]. Mathematically, the \(L_{dn}\) noise metric is expressed by \[26\]

\[
L_{dn} = 10 \log_{10} \left( \frac{1}{T} \left( t_d \cdot 10^{L_d/10} + t_n \cdot 10^{L_n+10/10} \right) \right)
\]

where \(T\) denotes the total time period (i.e., 24 h); \(t_d\) and \(t_n\) denote the number of hours during the day and night, respectively. By default, \(t_d\) and \(t_n\) are equal to 15 and 9 h, respectively.

Presently, the \(L_{dn}\) noise metric is commonly used only in the US alongside the \(L_{den}\) noise metric \[19\]. In other countries, the \(L_{den}\) noise metric is generally preferred because of the separation between evening and night.

### 2.3. Concluding Remarks

This section has defined the aircraft noise metrics commonly used to assess environmental impact, serving as a prelude to subsequent sections. There are two types of noise metrics—single event and cumulative. The former quantifies the noise level at a given observer location with respect to a single flight event, while the latter quantifies the noise level at a given observer location with respect to the time period (e.g., daily, monthly, or annually). Although different noise metrics are available for consideration, some are still more popular. The maximum noise level \(L_{\text{max}}\) is generally preferred as the single event noise metric, while the day–evening–night noise level \(L_{\text{den}}\) is widely adopted internationally as the cumulative noise metric.

Despite the popularity of some noise metrics, it is important to know that no noise metric is the best. Apart from conventional noise metrics, different sound quality metrics are also available for consideration \[29\]. Sound quality metrics are believed to provide closer agreement with community annoyance compared to conventional noise metrics \[30–32\]. Until they are well-established, international standards still rely on conventional noise metrics. Eventually, the noise metric should be appropriately chosen based on the requirements of the scenario. When in doubt, international standards and current literature should be referenced for guidance.

### 3. Effects of Aircraft Noise in the Built Environment

This section overviews how aircraft noise can affect the built environment in two key areas—public health (Section 3.1) and property value (Section 3.2). Note that this section serves as an overview instead of a review. Hence, the discussions are briefly conveyed in a broad sense. At the end of this section, clarity should be established on the need to emphasize prediction and management of aircraft noise from the outset of urban planning.

#### 3.1. Public Health

Noise pollution, in essence, has been associated with health problems regardless of age group. Since public health is at stake, research in this area has been extensively conducted over the past decades, showing evidence that chronic noise exposure can lead to health problems like noise-induced hearing loss, sleep disturbance, annoyance, cardiovascular diseases, and cognitive impairment in children \[33\]. Among these problems, noise-induced hearing loss remains the most prevalent \[34, 35\]. Mental health, hormone changes, metabolic disorders, and adverse birth outcomes are believed to be additional problems associated particularly with chronic aircraft noise exposure albeit conclusive evidence is lacking in the current literature \[27, 33, 36, 37\]. These health problems are summarized in Fig. 2. In modern society, the mass media has created awareness to majority of the general public on the harmful health effects of noise exposure. At the very minimum, the general public should have some awareness of the relationship between noise exposure and hearing loss.

The noise produced by jet aircraft can be as loud as 130–140 dBA \[38\]. If aircraft marshallers are not equipped with any hearing protection device, the noise level can rupture the eardrums and cause permanent hearing damage. Nonetheless, it is unlikely for such incident to occur with proper workplace safety regulations \[39\]. In the context of built environment, the World Health Organization (WHO) \[40\] provides recommendations serving as guidelines for policymakers to protect the public health from aircraft noise. Established based on research evidence in the literature, the recommendations for the entire day (24-hour period) and at night are 45 dBA \(L_{\text{den}}\) and 40 dBA \(L_{dn}\), respectively. Chronic aircraft noise exposure exceeding these recommendations is believed

### Fig. 2. Summary of the direct and indirect health problems caused by chronic aircraft noise exposure. A weak association denotes lack of conclusive evidence in the current literature \[27, 33, 36, 37\].

| Direct Health Problems | Indirect Health Problems (Strong Association) | Indirect Health Problems (Weak Association) |
|------------------------|---------------------------------------------|---------------------------------------------|
| Noise-Induced Hearing Loss | Cardiovascular Disease | Adverse Birth Outcomes |
| Annoyance | Cognitive Impairment in Children | Metabolic Disorders |
| Sleep Disturbance | Mental Health | |

\(L_{\text{den}}\): Day–evening–night noise level; \(L_{dn}\): Day–evening noise level; \(t_d\): Number of hours during the day; \(t_n\): Number of hours during the night; \(T\): Total time period; \(L\): Noise level; \(\log_{10}\): Logarithm base 10; \(\text{dBA}\): Decibels re 1 W/m².
to cause adverse health effects. Being recommendations rather than regulations, it is still possible that the recommended values are exceeded without any intervention by the local policymakers [41,42].

3.1.1. Direct Health Problems

Among the three direct health problems listed in Fig. 2, residents usually complain about how aircraft noise has caused annoyance and sleep disturbance, affecting their quality of life. Despite being the most prevalent health problem caused by chronic noise exposure, complaints on noise-induced hearing loss are more common among employees in the aviation industry rather than residents in the built environment [43–46]. This is unsurprising because the job nature of some aviation employees (e.g., cabin crew and aircraft marshalls) may require them to be in close proximity to aircraft operations. For example, in a review limited to the airports in China [46], eight out of 10 studies reported noise-induced hearing loss found in aviation employees. The remaining two studies found no evidence in hearing deterioration among school children who were in proximity to an airport. This may suggest that the risk of noise-induced hearing loss in residents is expected to be lower because of the longer distance between them and the noise source.

A lower risk, however, does not imply no risk. In a clinical study conducted in Taiwan [47], audiometry results found that residents staying near to the airport showed signs of deterioration in hearing compared to those living much farther away. In another clinical study, the same research group [48] revealed that the children from a school located directly under the flight path showed obvious deterioration in hearing compared to those from a school located far from the airport. This finding is alarming because unlike adults, children are generally negligent about the harmful effects of chronic noise exposure. Hence, it is imperative for policymakers to intervene with noise mitigation measures especially for schools.

Annoyance and sleep disturbance are associated in a vicious cycle. The definition of the former can help to understand why. Annoyance is an unpleasant mental state of mind that is attributed to the negative psychological response of an individual due to interference with activities—sleep, for example [33]. The negative psychological response can be anger, disappointment, dissatisfaction, or frustration. Sleep disturbance can be the cause, while annoyance can be the effect, and vice versa. If someone is feeling annoyed, it will be difficult to return to sleep. If someone’s sleep is disturbed and finds it difficult to return to sleep, it will lead to annoyance. This explains why both annoyance and sleep disturbance are associated in a vicious cycle, and why both of them are usually studied together in the literature [49–52], Gjesteland [53] provided an overview of the metrics available to quantify community annoyance.

In Germany, a five-year survey [52] involving more than 11,000 residents (aged 35–74 years) revealed that aircraft noise caused up to two times more annoyance than that of other transportation noise (i.e., rail and road). Residents who were exposed to aircraft noise at night were reported to experience sleep disorders. Bronzaft et al. [54] found that residents who often experienced sleep disturbance due to nocturnal flights would perceive themselves with poorer health albeit not medically diagnosed. This perception of poorer health could be attributed to the feeling of tiredness, sleepiness, and annoyance in the next day, not to mention reduced cognitive performance [55].

Specific to the expansion of Leipzig/Halle Airport in Germany, Basner et al. [56] assessed the consequences of the airport’s plan to introduce heavy traffic of nocturnal flights (up to 60 flights per hour) and proposed three recommendations to the policymakers. Firstly, nearby residents should not be awakened by nocturnal flights more than once on average. Secondly, residents should avoid recalling awakenings as much as possible in the morning. Lastly, nocturnal aircraft noise should have minimal interference with the process of returning back to sleep. These recommendations served to minimize sleep disturbance of nearby residents, but the procedures to executing them were not elaborated.

In the viewpoint of policymakers, the purpose of such assessments is essentially to minimize potential complaints, lawsuits, and compensations as much as possible. For example, researchers were requested by the Government in the Netherlands to survey residents staying within a radius of 25 km from Amsterdam Airport Schiphol and assess the current ground sentiments ahead of the airport’s plan to expand [57]. Out of nearly 12,000 residents, 5% of them had lodged official complaints to the Government. Among this group of residents, 60% of them felt highly annoyed and had their sleep disturbed at night. Reportedly, residents resorted to signing petitions and attending anti-campaigns to express their unhappiness and oppose the airport expansion plan. Some residents even planned to relocate. Relocation to avoid the issue entirely seems to be a viable option for residents who wish to take the matter into their own hands [42]. As emphasized by van Wiechen et al. [57], although the small population size which lodged official complaints could not truly represent the entire residential area, it could still provide the Government with an indication of the concern to address in a localized community.

In the other way round, noise annoyance complaints have also motivated assessment studies to emphasize and flag up the issue to the policymakers. For example, the Manchester Airport, England, has received a large volume of complaints on annoyance and sleep disturbance over eight years from 1991 to 1999. Realizing the need to minimize annoyance and sleep disturbance in nearby residents, Hume et al. [58] analyzed the complaints to find trends that could serve as the basis of recommendations for the airport to improve flight management. Notably, they found a surge in complaints during the night at 12 am and the early morning at 6.30 am. In one of the years (1998), there were 2,072 complaints but 594 residents. They discovered the presence of serial complainers who contributed to the surge. A detailed analysis revealed that majority of the residents complained up to two times, while three residents complained numerous times such that they contributed to 41% of the total complaints. Furthering this study, Hume et al. [59] discovered that flight events from 11 pm to 6 am resulted in five times more complaints than those from 6 am to 11 pm. The research group hoped that the findings could convince the airport to improve flight management, minimizing annoyance and sleep disturbance in nearby residents. Separately, Fidel et al. [60] also reported how a large volume of complaints may be contributed by a small number of serial complainers. It does not necessarily indicate that majority of the residents were annoyed and disturbed by aircraft noise. But, it can still indicate the issue among a localized community.

At night, residents are more sensitive to aircraft noise than during the day because of the low background noise. During the day, the aircraft noise in the housing estates may be masked by surrounding noise sources that are much closer. This is especially the case when the aircraft is at high altitude (i.e., nearing the end of a takeoff process or just starting to descend from the cruising altitude). In a survey involving more than 700 residents within 100 m radius from Gimpo and Gimhae International Airports in South Korea, Lim et al. [50,61] found that 85% of the residents were annoyed by aircraft noise. For the same aircraft noise level, residents from noisier neighborhoods experienced less annoyance compared to those from quieter neighborhoods, suggesting how background noise may influence community annoyance especially at night.

At this juncture, the overview of the direct health problems listed in Fig. 2 should have provided a better understanding in
how chronic aircraft noise can cause annoyance and sleep disturbance among residents in the built environment. Although noise-induced hearing loss is reportedly less likely, it must be emphasized that a low risk does not imply no risk. In the next section, an overview of the health problems strongly associated with annoyance and sleep disturbance is provided.

3.1.2. Indirect Health Problems (Strong Association)

By means of clinical studies and surveys, researchers have invested a tremendous amount of resources to find conclusive evidence in associating annoyance and sleep disturbance with various adverse health effects (Fig. 2). Cardiovascular diseases and cognitive impairment in children are two health problems in which research has found conclusive evidence to establish a strong association with annoyance and sleep disturbance [33].

Babisch [62] developed a flow diagram (Fig. 3) used in epidemiological noise research to describe the simplified chain reactions that associate transportation noise exposure with cardiovascular diseases. The flow diagram shows how annoyance and sleep disturbance can induce stress response in humans, leading to biological risk factors that eventually manifest cardiovascular diseases. As highlighted by Babisch [62], most studies have found consistent evidence to conclude that the risk of manifesting cardiovascular diseases increases with higher noise level. Babisch [62] added that research focus should no longer be on whether noise exposure leads to cardiovascular diseases, but rather to what extent.

In a cross-sectional study, Black et al. [63] compared the stress and hypertension reported by residents in two neighborhoods—one was near Sydney Airport, while the other was unaffected by aircraft noise. Expectedly, Black et al. [63] found that residents staying in proximity to the airport reported more cases of stress and hypertension compared to those unaffected by aircraft noise. Later, Hansell et al. [64] reported another study boasting a surveyed population of 3.6 million residents staying in the vicinity of Heathrow Airport, London. Based on the large sample size, the study aimed to establish conclusive association between aircraft noise exposure and the risk of cardiovascular diseases. Without differentiating between day and night flights during data analysis, Hansell et al. [64] confirmed that the louder the aircraft noise, the higher the risk of cardiovascular diseases—consistent with what Babisch [62] had later reviewed and highlighted. Considering such strong association, Hansell et al. [64] urged policymakers to be mindful of the potential implications in airport management plans.

Concurrently, in the United States, Correia et al. [65] reported another cross-sectional study that surveyed an even larger sample size (6 million) than that considered by Hansell et al. [64]. The demographic was, however, limited to elderly residents aged 65 years and older. Considering residential areas surrounding 89 airports, the elderly residents were chosen based on the criterion that they were exposed to aircraft noise of at least 45 dBA (Ldn) for the entire day (24-hour period). From the results, Correia et al. [65] established that the louder the aircraft noise in a neighborhood, the higher the hospitalization rate for cardiovascular diseases. This is consistent with the conclusion made by Hansell et al. [64]. Like how Hansell et al. [64] did not differentiate between day and night flights during data analysis, Correia et al. [65] emphasized the importance of pursuing such differentiation because nocturnal flights are believed to adversely affect cardiovascular health more significantly. Shortly, Münzel et al. [66] placed the same emphasis in a review article on the cardiovascular effects of environmental noise exposure.

The association between nocturnal aircraft noise and cardiovascular health—particularly hypertension—was assessed in a longitudinal study conducted in Europe [67]. Known as the Hypertension and Exposure to Noise Near Airports (HYENA) study, the data collected over two years (2004–2006) aimed to establish conclusive association between aircraft noise exposure and the risk of hypertension. The study was targeted at nearly 5,000 middle age residents (aged 45–70 years) who stayed near to six major airports over the past five years. Based on blood pressure measurements, Jarup et al. [67] concluded that nocturnal aircraft noise could cause sleep disturbance, leading to significant increase in blood pressure.
Being one of the biological risk factors (Fig. 3), the association between nocturnal aircraft noise and the risk of hypertension was established. Seven years later, Dimakopoulou et al. [68] followed up on the HYENA study to strengthen the association further based on diagnostic data. Albeit limited to residents in one of the six cohorts (Athens, Greece), the risk of stroke was reported to increase as well. Recent follow-ups [69,70] on the HYENA study reported that individuals with higher sensitivity to nocturnal aircraft noise may have higher risk of hypertension.

Separately, Eriksson et al. [71] found that gender could influence the risk of hypertension as well. The longitudinal study followed nearly 5,000 residents (aged 35–56 years) over 10 years in Stockholm, Sweden. More than half of the residents had a family history of diabetes. To avoid any bias, residents prescribed with hypertension medication at the baseline were excluded. Based on a threshold of 60 dBA ($L_{den}$), 80% of the residents complained about annoyance. Lowering the threshold to 50 dBA ($L_{den}$), more men (36%) felt annoyed than women (29%). Excluding smokers, blood pressure measurements showed that men had higher risk of hypertension due to chronic aircraft noise exposure compared to women.

In children, studies have also reported the increase in blood pressure due to aircraft noise exposure albeit the association with the risk of hypertension remains weak at this point in time [72]. On the other hand, research has found conclusive evidence to associate aircraft noise exposure with cognitive impairment in children especially reading comprehension [33]. In South Africa, Saebi et al. [73] assessed how chronic aircraft noise exposure would affect reading comprehension in children depending on whether English was their primary or secondary language. The assessment involved nearly 800 children divided into two groups—one had frequent aircraft noise exposure, while the other did not. The results showed that chronic aircraft noise exposure led to poorer reading comprehension in children with English as their primary language compared to those with English as their secondary language (i.e., native language as primary). In the latter group, no evidence was found to show that reading comprehension was affected, suggesting the possibility of fluency being an external factor that may contribute to the performance of reading comprehension in children. This correlates well with another study [74] which found that children exposed to aircraft noise made more mistakes in a written test compared to those who were not. The distribution of the mistakes skewed toward the difficult questions. The cross-sectional study considered 553 children who came from 24 primary schools around Amsterdam Airport Schiphol, Netherlands.

The association between chronic aircraft noise exposure and cognitive impairment has been extensively studied in Europe [75–81]. By studying children from 10 primary schools around Heathrow Airport, London, Haines et al. [75] also reported that children exhibited cognitive impairment only for the difficult questions in a cognitive test. The underlying reason was attributed to the annoyance caused by aircraft noise exposure. Later, Matsui et al. [76] observed similar outcomes in children who were at home. Stansfeld et al. [77] expanded the cross-sectional study into a cross-national study involving children from schools in the Netherlands, Spain, and the United Kingdom. The observations were consistent in showing poorer reading comprehension among children who were exposed to aircraft noise. This study arrived at a conclusion that schools located in the vicinity of an airport does not provide a conducive environment for education. Clark et al. [78] reported the first longitudinal study on the topic by following up on the children who took part in the earlier study six years ago [75]. By then, the children had progressed to secondary schools. As such, only children in secondary schools around the same airport were surveyed. The results showed that the children continued to exhibit poorer reading comprehension and felt more annoyed by aircraft noise than before. Clark et al. [78] further emphasized the conclusion made by Stansfeld et al. [77] in which the environment for education must be conducive.

Apart from reading comprehension, the same research group [79] also studied the effects of chronic aircraft noise exposure on short- and long-term memory in children. The study leveraged on the old Munich–Riem Airport’s termination and the new Munich Airport’s opening at a different location. The children in both locations were surveyed thrice—six months before the termination/opening, one year, and two years after the termination/opening. The results revealed that children residing near the new airport started to develop short- and long-term memory impairment. For those residing near the terminated airport, short- and long-term memory started to improve. This finding was later reinforced by Matheson et al. [80] in a cross-national study that involved children from schools in the Netherlands, Spain, and the United Kingdom. Stansfeld et al. [81] further analyzed the same data obtained by Hygge et al. [79] and found marginal drop in cognitive performance in children due to nocturnal aircraft noise exposure. Again, the need to ensure a conducive environment for education was reiterated, hoping that policymakers would look into this matter.

At this juncture, the overview should have provided a better understanding in how cardiovascular diseases and cognitive impairment in children are strongly associated with chronic aircraft noise exposure. As this article aims to emphasize the need for prediction and management of aircraft noise from the outset of urban planning owing to the negative effects—supported by strong evidence—in the built environment, the remaining health problems currently shown to have weak association are only briefly discussed for the sake of completeness in the next section.

### 3.1.3. Indirect Health Problems (Weak Association)

Apart from cardiovascular diseases and cognitive impairment in children, studies have also attempted to associate chronic aircraft noise exposure with other health problems (Fig. 2). These include adverse birth outcomes, metabolic disorders, and mental health. In a white paper on aviation noise, Sparrow et al. [33] discussed how conclusive evidence remains lacking in the literature to support the association between chronic aircraft noise and the respective health problems.

On adverse birth outcomes, Nieuwenhuijsen et al. [82] recently provided a systematic review under WHO’s continuous efforts to update environmental noise guidelines in Europe. It aimed to assess the evidence in associating aircraft and traffic noise with adverse birth outcomes—namely preterm birth, low birth weight, and congenital anomalies. Over 30 years, only six studies on aircraft noise exposure were reported—four on preterm birth and low birth rate, and two on congenital anomalies. On preterm birth and low birth rate, Nieuwenhuijsen et al. [82] discussed how the four studies had limitations and provided weak evidence to establish an association with aircraft noise exposure. On congenital anomalies, the two studies from the 1970s reported inconsistent results—one showed weak association, while the other did not. Since then, further studies have been highly limited.

In another systematic review under the same WHO’s continuous efforts as Nieuwenhuijsen et al. [82], van Kempen et al. [83] found only two studies from the same year (2014) that specifically focused on associating chronic aircraft noise exposure with metabolic disorders. Both studies found that the risk of diabetes was independent of chronic aircraft noise exposure. In one of the two studies, obesity was found to be associated instead based on results from multiple follow-ups over 8–10 years. Further studies are required to strengthen this association.

Lastly, on mental health, studies have shown minimal influence of chronic aircraft noise exposure on mental health. Dreger et al.
reported the first study in Germany to investigate whether chronic aircraft noise exposure affects mental health in children at home. Instead of objective measurements, parental annoyance reports were used to determine if the children were exposed to aircraft noise. No evidence was found to establish any association. Again, in Germany, Seidler et al. [85] reported the first study to assess a different age group. Targeted at residents aged 40 years and older, evidence was found to associate chronic aircraft noise exposure with depression. However, the evidence was deduced from health insurance claim records, implying that the conclusion was not firm. Shortly, in a cross-sectional study involving nearly 200,000 residents staying near George Best Belfast City Airport, Ireland, Wright et al. [36] concluded marginal influence of chronic aircraft noise exposure on mental health.

Owing to highly limited studies and inconsistent findings, it is evident that chronic aircraft noise exposure is weakly associated with adverse birth outcomes, metabolic disorders, and mental health at this moment.

3.2. Property Value

Other than public health, aircraft noise is known to affect housing prices as well. On the contrary, some researchers [86–89] argued that the correlation between aircraft noise and property value is weak. Whether it is a weak or strong correlation, aircraft noise is still largely found to affect housing prices negatively [90]. As such, an overview of this topic is still included for the sake of completeness albeit relevant studies are limited in the literature.

Naturally, the property value of housing estates that are situated in proximity to an airport or are directly under the flight path suffers the most. A common way to quantify the monetary relationship between aircraft noise and property value is the Noise Depreciation Index (NDI). The NDI stems from the hedonic pricing method and is defined by the percentage loss in property value per unit increase in aircraft noise level (%/dB) [91,92]. For example, in the same neighborhood, if the housing estate is exposed to an average noise level of 70 dB and has a NDI of 0.5%/dB, its selling price is expected to be 5% less compared to that of another housing estate that is exposed to an average noise level of 60 dB. Evidently, the loss in property value can be quite substantial for housing estates that are located near to an airport or are directly under the flight path.

Table 1 summarizes the NDI reported in North America, Europe, Australia, and Asia. The intention of this table is to present the general trend rather than to analyze location-specific data, which is beyond the scope of this overview. For more details on the latter, the work of He et al. [93] should be referred to. As such, the data presented in Table 1 is adapted from He et al. [93] and reorganized to show the NDI range and to include recent studies [94,95]. Apart from He et al. [93], several other reviews of this topic [90,91,96,97] have similarly reported that research effort has been ongoing since the 1970s with focus largely limited to Australia, Europe, and especially North America. This section has provided an overview of how aircraft noise can affect the built environment in two key areas—public health and property value. At this juncture, the overview should have created more awareness regarding how both areas are negatively affected.

On public health, this overview has outlined the direct and indirect health problems associated with chronic aircraft noise exposure. At this moment, studies have found conclusive and consistent evidence to associate chronic aircraft noise exposure with annoyance, sleep disturbance, noise-induced hearing loss, cardiovascular diseases, and cognitive impairment in children. A strong association has yet to be established for adverse birth outcomes, metabolic disorders, and mental health.

On property value, this overview has shown that aircraft noise has been contributing to the depreciation of housing estates that are in proximity to an airport or are directly under the flight path. Whether the depreciation rate is small or large, the monetary value can still be substantial considering that housing prices are typically high. Although such emphasis has been strong in North America,
Europe, and Australia since the 1970s, recent studies have suggested that the same emphasis is growing in Asia as well.

Owing to work-from-home arrangement, residents have become more aware of aircraft noise around the neighborhood in the daytime, not to mention increased noise exposure. Anticipating that work-from-home arrangement may likely become an integral part of workplace management moving forward, aircraft noise exposure may become one of the deciding factors in property acquisition especially when chronic exposure can lead to health problems. As such, it is imperative for urban planning professionals to start considering aircraft noise exposure as a long-term issue in the built environment. To minimize noise-induced public health issues, property depreciation, noise complaints, and even monetary compensations, provisions for aircraft noise prediction and management should be emphasized especially from the outset of urban planning. Ultimately, one of the ways to resolve the problem should not be recommending residents to move out of the neighborhood if they are unable to tolerate aircraft noise [102].

4. Aircraft Noise Prediction Models

Having understood the implications of chronic aircraft noise exposure in the built environment, it is of interest to see how aircraft noise can be predicted in a practical manner so that decision can be quantitatively made on whether precautionary actions should be taken from the outset of urban planning. Following a background on the two categories of aircraft noise prediction models (Section 4.1), Section 4.2 discusses the category that is relevant to urban planning professionals. Lastly, Section 4.3 provides clarity on how the relevant models have been used in urban planning by reviewing case studies reported over the last decade. This 10-year coverage (2011–2021) helps to limit the scope and ensure recency.

4.1. Categories of Prediction Models

Different aircraft noise prediction models have been developed over the past decades. Depending on the users, these models are utilized to achieve different desired objectives. Aircraft manufacturers are interested in highly detailed simulations that allow to minimize noise at component level. Airport operators are more interested in simulating cumulative noise metrics around the airport to comply with regulations. Urban planning professionals make use of predictions to assess aircraft noise exposure in the built environment surrounding the airport. Except for component-level analysis, the results are typically presented in the form of noise maps.

Current models can be divided into two categories—scientific (or theoretical) models and best practice models [103]. Scientific models are capable of predicting the absolute noise level of an aircraft with unconventional configurations, new designs, or new procedures in a single flight event. Being usually proprietary, scientific models may not be widely accessible to interested users. Aircraft manufacturers prefer scientific models because of the need to constantly innovate and develop cutting-edge solutions.

Best practice models depend nearly exclusively on pre-existing databases. They only document the methodology in aircraft noise prediction. A software must be developed to truly perform any predictions. The Aviation Environmental Design Tool (AEDT) was developed by the US Federal Aviation Administration (FAA) based on ICAO Doc. 9911 [115], ECAC Doc. 9911 is essentially the main model that guides the development of ICAO Doc. 9911 and AzB. Originally developed based on SAE-AIR-1845 [116] (now superseded by SAE-AIR-1845A [117]), the latest edition of ICAO Doc. 9911 is largely adapted from ECAC Doc. 29 [20,118]. Likewise, AzB is partly adapted from ECAC Doc. 29, but prescribed with additional criteria that must be met according to the German Act on Protection against Aircraft Noise [119]. AzB is intrinsically not a comprehensive model; it only defines how noise maps should be calculated and what data should be needed [20].

It must be highlighted that all three models are not intrinsically ready-made software. They only document the methodology in aircraft noise prediction. A software must be developed to truly perform any predictions. The Aviation Environmental Design Tool (AEDT) was developed by the US Federal Aviation Administration (FAA) based on ICAO Doc. 9911 [115], AEDT [120] supersedes the widely used Integrated Noise Model (INM) [121]—a legacy tool that was also developed by FAA. By unifying other legacy tools, AEDT can predict not only aircraft noise, but also fuel consumption, emissions, and air quality consequence. AEDT relies on NOISEFILE, ANP, and BADA databases.

Relying on ANP database, the Aircraft Noise Contour Model (ANCON) was developed by the UK Civil Aviation Authority (CAA) based on ECAC Doc. 29 [20]. ANCON was last updated in 1999 [122]. Future development plans are reported in the documentation, but no update has been reported for more than two decades. Despite this, ANCON remains relevant to date [69,70] and is referred to as the national standard model of the United Kingdom for urban planning around airports [103].

Unlike AEDT and ANCON, AzB relies on its own database of civil and military aircraft models in addition to ANP database [119,123].

Table 3

| Category       | Model Name | Developer Name | Country of Origin |
|----------------|------------|----------------|-------------------|
| Scientific     | ANOPP [107]| NASA           | USA               |
|                | CARMEN [108]| ONERA          | France            |
|                | FLIGHT [109]| University of Manchester | England |
|                | PANAM [110] | DLR            | Germany           |
|                | SAFT [111] | Chalmers University of Technology | Sweden |
| Best Practice  | sonAIR [112]| Empa          | Switzerland       |
|                | AzB [113]  | ECAC           | Germany           |
|                | Doc. 29    |                | France            |
|                | [20,114,115]|                |                   |
|                | Doc. 9911  | ICAO           | Canada            |

Table 3 lists the notable scientific and best practice models for aircraft noise prediction. According to Filippone [103], there are several other scientific models with highly limited documentation in the literature. Such models are not listed in Table 3 due to lack of information. Nonetheless, as this review article is primarily crafted for urban planning professionals, the scope is limited to the best practice models—discussed in the next section—in view of relevancy.

4.2. Best Practice Models

Currently, there are three notable best practice models—AzB by the German Aerospace Center (DLR), Doc. 29 by the European Civil Aviation Conference (ECAC), and Doc. 9911 by the International Civil Aviation Organization (ICAO). ECAC Doc. 29 is essentially the main model that guides the development of ICAO Doc. 9911 and AzB. Originally developed based on SAE-AIR-1845 [116] (now superseded by SAE-AIR-1845A [117]), the latest edition of ICAO Doc. 9911 is largely adapted from ECAC Doc. 29 [20,118]. Likewise, AzB is partly adapted from ECAC Doc. 29, but prescribed with additional criteria that must be met according to the German Act on Protection against Aircraft Noise [119]. AzB is intrinsically not a comprehensive model; it only defines how noise maps should be calculated and what data should be needed [20].
DLR has been maintaining and updating the database with additional aircraft models. There are also plans in the pipeline to improve the methodology [113]. The implementation of AzB is realized via INM [124]. Since AzB was developed according to the German Act on Protection against Aircraft Noise, its relevancy is strictly limited to Germany, not to mention that the technical documentation is published in German [125].

At this juncture, there should be clarity on how ECAC Doc. 29 is essentially the main model associated with other best practice models and the software developed based on these models. This association is illustrated in Fig. 4. Despite being the main model, ECAC Doc. 29 relies on large assumptions in the computation. Hence, it can only provide reasonably accurate predictions. To improve the accuracy, it is imperative to employ further developments to the base model with less reliance on the default values given in ANP database [126]. On a side note, there are well-developed—but costly—commercial software that allows users to intuitively perform predictions based on the desired model. Leading examples include SoundPLAN and CadnaA. These software provide additional capabilities to easily assess the scenario according to a combination of different models and transport modes. In the next section, case studies reported over the last decade are reviewed to provide further clarity on how the relevant models have been used in urban planning.

### 4.3. Usage of Predictions in Urban Planning

Based on the case studies reported over the last decade, best practice models have been used in urban planning to evaluate the cost of introducing noise control measures in the built environment, to assess the implications of airport expansion on surrounding neighborhoods, and to justify policy proposals.

In São Paulo, Brazil, da Silva and de Arantes Gomes [127] reported that the cost to implement soundproof windows in housing estates surrounding 29 airports was estimated to be as high as US$28,000. Using INM, predictions provided an indication to the number of affected residents due to the noise exposure threshold of 55 dBA ($L_{dn}$). If the noise exposure threshold was set at 70 dBA ($L_{dn}$), the estimated cost would be US$4,000. The study aimed to convince the local policymakers in taking appropriate actions to minimize noise exposure in the built environment. However, recent studies [128,129] done to further convince the local policymakers suggest that the emphasis in this area remains minimal to date.

In Semarang, Indonesia, Andarani et al. [23] reported that the local policymakers have recently started to place emphasis on minimizing aircraft noise exposure in the built environment. As a pilot study, INM was used to provide noise exposure predictions in the vicinity of Ahmad Yani International Airport. To assess the severity, the land area around the airport was partitioned according to different ranges of WECPNL (defined in Section 2.2.1). Noise control measures were highly recommended to the local policymakers for the zone with 75–80 WECPNL because of high residential density.

The local policymakers in Hanoi, Vietnam, have also shown recent interest in establishing a national standard to minimize aircraft noise exposure in the built environment. In a pilot study, Nguyen et al. [130] demonstrated the use of INM to gain insight into the amount of noise that the residents around Noi Bai International Airport were exposed to before and after its opening. This study served as the foundation for subsequent plans to do likewise for the remaining airports in the country. Recently, based on the same airport, Bui et al. [131] included military aircraft in the predictions. There were, however, some challenges. As information on the flight path was unavailable and could not be measured via a Automatic Dependent Surveillance-Broadcast (ADS-B) for security reasons, only straight flight paths were considered for both takeoff and landing. Since ANP database is limited to civil aircraft models, measurements were required to obtain the noise-power-distance (NPD) relationship for the military aircraft ( Sukhoi Su–22).

Licitra et al. [132] managed to address the challenge in missing information by recording the flight path of military aircraft via an ABS-B. However, no discussion was provided on whether the NPD relationship for the military aircraft were measured or sourced. Using INM, the predictions provided an estimation to the number of residents that could potentially be affected by civil and military aircraft taking off from and landing at Pisa International Airport. This enabled the airport operator to decide whether additional noise control measures were required due to increased air traffic.

Ideally, it may be easier to achieve comprehensiveness of the military aircraft database through a joint collaboration between the defense force and a national research institute. For example, in Italy, the Italian Air Force and the Italian Aerospace Research Center collaborated to build up a database—known as MILNOISE—after many years of extensive measurements [133]. Whenever a new aircraft model joined the fleet, the database was updated with new measurements [134]. As most information was made available through the joint collaboration, predictions could be efficiently performed to reveal potential noise pollution around airbases. Consequently, noise control measures could also be proposed timely. Similar collaborative efforts were also reported in the United States [135–139] and Germany albeit critical modeling details are typically undisclosed. Despite the advantage of joint collaborations, some countries may not be able to provide strong justifications in doing so due to limited resources and lack of current emphasis on minimizing aircraft noise exposure in the built environment [140].

In Tehran, Iran, Sadr et al. [141] used INM alongside in–house optimization codes to predict the potential noise pollution around Imam Khomenei International Airport and a nearby neighborhood. The former and the latter were planned for concurrent expansion and redevelopment, respectively, over the next few years. Forecast results revealed that residents staying in the vicinity of the two sites would experience increased noise exposure with aircraft noise being the main contributor. Residents would also be affected especially at night due to higher air traffic. Based on the findings, Sadr et al. [141] recommended that the airport operator should preempt the problem. Motivated by the same objective, Sadr [142] further assessed other scenarios of the development plan to reinforce their earlier findings and reiterate their recommendations to the airport operator. In this later study, CadnaA was used for predictions instead of INM. Case studies with the same objective were also reported for Narita International Airport [143].
Athens International Airport [144], and Istanbul Atatürk Airport [145] in Cyprus, Greece, and Turkey, respectively.

Instead of proposing noise control measures to the inland airport operator, Yan et al. [146] put forth a comprehensive analysis to justify the benefits of offshore airports over inland airports. Between the expansion of Dalian International Airport and the construction of an offshore airport in Jinzhou Bay, the latter was predicted to affect nearly three times less residents than the former based on the noise exposure threshold of 75 WECPNL. To support the proposal further, Yan et al. [146] discussed how offshore and semi-offshore airports have been adopted by many Asian countries to minimize aircraft noise exposure in the built environment.

4.4. Concluding Remarks

This section has discussed the two categories of aircraft noise prediction models—scientific and best practice. The latter allows aircraft noise predictions to be achieved in a practical and straightforward manner compared to the former. As such, best practice models are recommended for urban planning professionals whose objective is to get a quick sensing of any potential aircraft noise issue in the built environment around the airport of interest. Although several best practice models exist, current commercial software—SoundPLAN and CadnaA, for example—integrates most of the models within one platform to provide the user with added convenience for predictions to be performed. Consequently, timely decision can be made to take precautionary actions from the outset of urban planning. A review of cases studies reported over the last decade has provided clarity on how the best practice models have been used in urban planning to minimize aircraft noise in the built environment.

5. Aircraft Noise Management

Knowing the implications of chronic aircraft noise exposure in the built environment and how it can be predicted in a practical manner, it is of subsequent interest to understand how aircraft noise can be managed. Section 5.1 first provides a background of the Balanced Approach in managing aircraft noise. Next, Section 5.2 reviews the state-of-the-art (5-year coverage) in aircraft noise control measures that could potentially be incorporated in housing estates for better acoustic comfort.

5.1. The Balanced Approach

The Balanced Approach, as detailed in ICAO Doc. 9829 [147], refers to the management of aircraft noise based on the consideration of four key elements—namely noise reduction at source, land-use planning and management, noise abatement operational procedures, and operating restrictions. In principle, all approaches should be considered equally.

On the first approach, ICAO Doc. 9829 [147] limits the scope of noise reduction at source via the adoption and constant revision of noise certification standards—ICAO Annex 16 [148], for example—which must be complied by airport operators. Despite this limitation in scope, ICAO recommends two additional approaches that could be considered. Firstly, aircraft manufacturers should constantly innovate to develop new technologies for quieter aircraft. A notable example is the serrated engine nacelles of Boeing 787 [149]. Jointly developed with the National Aeronautics and Space Administration (NASA) and General Electric, the serrated engine nacelles reduce jet noise by influencing how outlet air mixes with the surroundings. Secondly, new technologies should be retrofitted throughout the life cycle of the aircraft to improve the overall noise performance of the fleet in the airport.

On the second approach, ICAO Doc. 9829 [147] recommends the need for proper planning and management so that incompatible land use can be avoided. In this context, incompatible means that schools and housing estates should not be built near to an airport. Instead, the land may be reserved for commercial and industrial use (i.e., compatible use). To differentiate between compatible and incompatible use, the widely recognized way is by predicting the aircraft noise map around the airport in terms of day-night noise level ($L_{eq}$), which is defined in Section 3.1.2. Schools and housing estates should not be built in any areas exceeding 65 dBA ($L_{eq}$). As emphasized in ICAO Doc. 9829 [147], the airport operator must work closely with local authorities to ensure successful land-use planning and management.

The third approach refers to the procedures associated with ground-based and in-flight operations. ICAO Doc. 9829 [147] recommends that this element should only be considered if there is an existing noise issue to address. Any proposed changes to the operating procedures must not compromise safety, which is the utmost priority in aviation. For example, preferential runways and routes can be considered so that the flight path is not near to noise-sensitive areas. Additionally, cutback thrust and idle reverse thrust can be considered during takeoff and landing, respectively. On the ground, safety inspections of aircraft engines involve operating them at high power, producing loud noise. A possible noise abatement measure is to conduct the inspections at areas that are assessed to not create any issue to noise-sensitive areas around the airport. According to the meta-analysis in a review paper [150], the third approach—among other approaches—was found to be considered the most by airport operators across all continents except Antarctica in 2009.

On the last approach, ICAO Doc. 9829 [147] urges the consideration of operating restrictions only as the last resort—or at least not as the first choice of approach—in managing aircraft noise. In this approach, aircraft operations can be prohibited during certain time of the day. For instance, airport operators can consider prohibiting departure and arrival flights between 11 pm and 6 am to prevent sleep disturbance. As an extreme measure, airport operators can consider to ban certain aircraft from operating entirely. On the other hand, airport operators can consider reducing the amount of air traffic over a period of time. Nonetheless, it must be emphasized that this approach could adversely impact the economy if not executed properly, explaining why it should only be considered only if all possible aircraft noise management approaches are explored.

5.2. State-of-the-Art in Aircraft Noise Control Measures

The Balanced Approach, which is related to policy proposals, may not be entirely applicable depending on the circumstances [151,152]. Hence, it may also be feasible to address the issue by implementing noise control measures at the transmission path of the noise—that is, the façade and morphology of housing estates. This section reviews the state-of-the-art in both noise control measures in Sections 5.2.1 and 5.2.2, respectively.

5.2.1. Open Windows

Among the various building façade elements, the weakest element in reducing noise is the window. Conventionally, soundproof windows—double-glazed windows, for example—are installed to effectively reduce environmental noise—not only aircraft noise—entering the apartment. However, this type of windows must be fully closed to achieve their full potential in noise reduction. Owing to the COVID-19 pandemic, it is now crucial to ensure that the living space is constantly well-ventilated to minimize the risk of transmission [153]. For conventional soundproof windows, increased ventilation means increased noise exposure. Conversely,
the state-of-the-art in open window concepts has shown otherwise with the possibility of having both increased ventilation and reduced noise exposure. The latter can be achieved through passive or active means—both of which are reviewed in this section with emphasis placed on those showing notable low-frequency performance ($\leq 500$ Hz). This is the frequency range in which the energy content of aircraft noise is concentrated at [154,155]. Table 4 summarizes the window concepts discussed in this section.

Recent studies have shown the potential of plenum windows for low-frequency environmental noise control. The concept for plenum windows is fundamentally the same as conventional double-glazed windows except that the former is designed to be partially opened instead of fully closed. Plenum windows are double-glazed windows with staggered openings that direct sound propagation along a duct-like path before entering the living space [164]. The windows can be oriented vertically or horizontally (Fig. 5). The original purpose of plenum windows was to provide both ventilation and noise reduction in high-rise housing estates of the tropical and subtropical zones where the weather is hot during most or some of the time. With recent emphasis on ventilation owing to the COVID-19 pandemic, plenum windows now have an expanded purpose and may find more applications internationally apart from Hong Kong [164,165].

Over the past five years, plenum windows have been studied in different configurations to enhance noise reduction albeit most studies focused on traffic noise rather than aircraft noise. Since aircraft noise is dominantly low-frequency ($\leq 500$ Hz), it is more challenging to mitigate compared to traffic noise in which the acoustic energy is concentrated at around 1 kHz. Nonetheless, some concepts have achieved notable noise reduction at below 500 Hz, suggesting potential application for aircraft noise mitigation.

Using a two-dimensional simulation model, Yu et al. [156] studied how the opening size and the separating distance of the glass panels would affect the window’s performance in reducing noise at low frequencies. To investigate the former, the opening size was varied at 15, 30, and 50 cm per unit depth while fixing the separating distance at 30 cm. To investigate the latter, the separating distance was varied at 20, 30, and 40 cm while fixing the opening size at 50 cm per unit depth. Results showed that smaller opening size and larger separating distance are beneficial in enhancing narrowband performance at low frequencies. For the opening size of 15 cm, the peak reduction (~24 dB) occurred at 500 Hz. For the separating distance of 40 cm, the peak reduction (~18 dB) occurred at 310 Hz. Later, Du et al. [166] reported a similar study that was done experimentally.

In the same study, Yu et al. [156] investigated the benefit of adding either micro-perforated panel or sound foam within the window. Based on a prescribed configuration of the micro-perforated panel, Yu et al. [156] studied how the air gap behind the panel would influence the window’s low-frequency performance. Simulated results showed broadband reduction of up to 31 dB between 310 and 500 Hz when the largest air gap (10 cm) was considered. The resulting window configuration may not be practical for application because the separating distance must be large enough ($\geq 50$ cm) to permit adequate ventilation. For the sound foam, experimental results revealed its benefit only at above 500 Hz.

Owing to the staggered openings, air exchange rate is expected to be poorer than conventional casement and sliding windows. To promote ventilation, Du et al. [157] introduced an array of eight fans within a vertical plenum window to mechanically draw air into the living space. Compared with a fully opened conventional casement window, the proposed plenum window enhanced the air exchange rate by around 5.8 times. Apart from the fans, the inner walls of the window frame were installed with a layer of sound foam. Regardless of whether the fans were turned on or off, noise reduction remained comparable across the studied frequency range (100–3,150 Hz). At low frequencies, the peak reduction (~26 dB) occurred at 400 Hz.

Lee et al. [158] highlighted that the key shortcoming of plenum windows is the limited number of design parameters available for performance tuning such that significant noise reduction can be achieved at the frequency range of interest. To address this shortcoming, Lee et al. [158] proposed to incorporate three square channels—or referred to as sonic crystal—within a horizontal plenum window. The channels also functioned as resonators, which were achieved via a slit in the longitudinal direction. On the contrary, the configurations of the channels were fixed throughout the work with no reports on any parametric study. Peak insertion loss (~1 dB) was reported at 250 Hz albeit parametric study could have yielded better performance [167].

Instead of sonic crystal, plenum windows can also be incorporated with labyrinthine array to introduce additional design parameters for performance tuning. Although several concepts

![Fig. 5. Schematic diagrams of typical plenum windows oriented (a) horizontally and (b) vertically. Dashed lines and shaded regions denote the staggered openings and glass panels, respectively. Arrows denote how sound propagates through the plenum windows from the environment (outdoor) to the living space (indoor).](image_url)

### Table 4
Summary of window concepts showing notable reduction at low frequencies ($\leq 500$ Hz) reported over the past five years (2016–2021).

| Authors          | Window Concept                      | Peak Reduction | Lab Test | Field Test |
|------------------|-------------------------------------|----------------|----------|------------|
| Yu et al. [156]  | Plenum + Micro-Perforated Panel     | ~31 dB at 500 Hz | No       | No         |
|                  | Plenum + Sound Foam                 | ~30 dB at 500 Hz | No       | No         |
| Du et al. [157]  | Plenum + Sound Foam + Fans          | ~26 dB at 400 Hz | No       | Yes        |
| Lee et al. [158] | Plenum + Sonic Crystal              | ~1 dB at 250 Hz  | Yes      | No         |
| Wang et al. [159]| Partial Plenum + Labyrinthine       | ~10 dB at 400 Hz | No       | Yes        |
| Lam et al. [160] | Single-Glazed Sliding + ANC (16-Channel) | ~2 dB at 500 Hz | Yes       | No         |
| Lam et al. [161] | Single-Glazed Sliding + ANC (24-Channel) | ~10 dB at 400 Hz | Yes       | No         |
| Lam et al. [162] | Top-Hung + ANC (4-Channel)          | ~7 dB at 190 Hz | No       | Yes        |
| Mirshekarloo et al. [163]| Top-Hung + Piezoelectric Films       | ~12 dB at 350 Hz | No       | Yes        |

* Based on a 1:4 scaled-down model.
were studied \[168,169\], notable low-frequency performance was only recently reported in the work of Wang et al. \[159\]. Wang et al. \[159\] proposed a concept combining single-glazed window (bottom portion) and plenum window (top portion). The plenum window was incorporated with a labyrinthine array consisting of 14 unit cells with differing dimensions. The space coiling mechanism of the array allowed the realization of noise reduction. Experimentally, based on a 1:4 scaled-down model of only the plenum window portion, the peak insertion loss (\(-10 dB\)) was achieved at 400 Hz. Considering practical applications, it may be challenging to fabricate the labyrinthine array in full-scale even with additive manufacturing technology. Moreover, the labyrinthine can potentially trap dust, causing maintenance issues.

It is widely known that active noise control (ANC) is effective in providing localized noise cancellation at low frequencies. This explains why ANC has been found in high-end commercial products—hearables and luxury cars, for example—that aim to cancel exterior noise within a small space. Recent advances in ANC application on open windows have shown the potential of noise reduction in living spaces albeit the overall set-up may seem highly sophisticated \[170\].

Lam et al. \[160\] introduced a 16-channel ANC system on a single-glazed sliding window and studied its effectiveness in noise reduction when the window was partially opened from one side. The secondary sources (i.e., speakers) were fixed on the window grille. At an opening of 30 cm, the active performance was not impressive compared to the passive performance of the fully-closed window. At 500 Hz, the former achieved about 2 dB reduction, while the latter provided about 13 dB reduction. Being a pilot study, one of the design intentions was not to cause excessive visual obstruction and affect air exchange rate. Hence, the speakers were not large enough to provide good noise cancellation at below 500 Hz. Separately, Lam et al. \[171\] complemented the experimental work with a parametric study of the ANC system via two-dimensional simulations. This numerical work supported that effective low-frequency noise control could be achieved with the right configurations.

Later, Lam et al. \[161\] improved the ANC system on the same single-glazed sliding window from 16-channel to 24-channel. In the laboratory study, the performance of the window in aircraft noise reduction was specifically evaluated. Again, the passive performance of the fully closed window was far superior than the active performance of the half-open window. However, if the comparison was limited to the half-open window, the ANC system could achieve up to about 10 dB reduction in aircraft noise at 400–500 Hz. At below 350 Hz, the reduction was marginal due to the size of the speakers.

Evidently, if low-frequency performance of the ANC system is paramount, the window will provide poorer ventilation and visibility of the outdoor environment. To address the latter, Lam et al. \[162\] proposed to incorporate the ANC system (4-channel) in a top-hung window. The design concept compromised on ventilation because the top-hung window was only a small portion of the entire casement window. Owing to the use of larger speakers, the window became aesthetically unpleasing. The concept successfully demonstrated the possibility of significant aircraft reduction of up to about 7 dB at 100–500 Hz, peaking at 190 Hz when the ANC system was turned on.

To improve the aesthetics of the top-hung window, Mirshekarloo et al. \[163\] proposed to replace the speakers with piezoelectric films. The films were adhered onto the glass panel. Being translucent, the top-hung window was more aesthetically pleasing than the concept of Lam et al. \[162\]. In a mock-up residential apartment, the experimental results showed that noise reduction was only achieved at specific frequencies—350, 420, and 500 Hz. The peak reduction (12 dB) occurred at 350 Hz.

### 5.2.2. Urban Morphology

In architecture, urban morphology refers to the main physical elements that collectively form the landscape of the city—buildings, parks, plants, and streets, for example. Urban morphology has been widely studied to establish its influence on traffic noise \[172\]. However, studies with specific focus on aircraft noise are highly limited \[173\] even if the 5-year coverage (2016–2021) extends for five more years (2011–2021) \[174\]. Recently, in a systematic review article, Joen \[172\] only found three of such studies reported over 18 years (2002–2020). Owing to literature scarcity, this section is mainly limited to the discussion of relevant findings associated with traffic noise that may motivate further studies to better establish the influence of urban morphology on aircraft noise. Two areas are discussed—vegetation and building envelope.

Based on a study in Wuhan, China, aimed to minimize traffic noise, Yuan et al. \[175\] recommended that during urban planning, emphasis should be placed on maximizing the amount of vegetation in residential areas wherever possible. To achieve the best results, the vegetation should include a variety of species at different heights, and be as dense as possible. Han et al. \[176\] provided consistent recommendations based on a study in Shenzhen, China.

Unlike the above studies that made use of correlation factors to draw conclusions, Ow and Ghosh \[177\] quantitatively reported the traffic noise reduction due to the insertion of a vegetative barrier between the road and the housing estates. In contrast to the recommendations of Yuan et al. \[175\], Ow and Ghosh \[177\] found that the vegetative barrier provided diminishing benefit with increasing vegetation density. Comparing between sparse and dense planting, the latter only provided additional traffic noise reduction of 1.2 dBA. Ow and Ghosh \[177\] also discovered that larger trunk diameters would provide more reduction regardless of vegetation density. For example, in dense planting, the reduction went from 3 to 10 dBA when the diameter was increased from 8 to 35 cm. Since aircraft noise is predominantly low-frequency, larger trunk diameters should be recommended over smaller trunk diameters because the latter may be acoustically transparent (i.e., much smaller in geometry than the longest wavelength of interest) to the sound propagation.

The restorative potential of vegetation is also believed to improve noise perception among residents \[178,179\] despite conflicting findings showing otherwise \[180\]. Focusing on aircraft noise, Lugten et al. \[179\] studied the effects of vegetation and water fountain on noise perception among participants in a virtual reality neighborhood. The neighborhood was realized via a head-phone and a head-mounted visual display. Whenever the aircraft noise was heard in the headphones, the environment would realistically animate an aircraft flying across the participant’s line of sight. With vegetation, most participants felt more pleasant when they saw the aircraft flying past the neighborhood. With the water fountain, the sound of moving water introduced masking effects, causing it to be perceived by the participants as the dominant noise source instead of the aircraft. Consequently, Lugten et al. \[179\] hoped that their study had revealed new avenues for urban planning professionals to further research on for improving aircraft noise perception in the built environment.

Conversely, Schäffer et al. \[180\] reported that increased vegetation in residential areas did not improve aircraft noise perception. To support this finding, two possible reasons were provided. Firstly, residents are constantly exposed to traffic noise daily such that it has become an inherent acoustic feature in the built environment. Aircraft noise, however, is intrusive and unpredictable. Secondly, as aircraft noise usually originates from a point in space that is much higher in altitude than the vegetation, residents are exposed to the noise under direct line of sight. This is especially true for residents staying at higher floors of the housing estate.
Evidently, the main limitation of vegetation lies in the height, which is unlikely taller than high-rise buildings.

The exterior surfaces of a building can function as either a sound absorber or a sound reflector depending on its profile and material. It is impractical to cover the building envelope with conventional sound absorbing material found in building interiors because of poor durability under different weather conditions. Hence, vegetation serves as a viable alternative. If the building envelope is covered with vegetation, it can provide sound absorption in the built environment [172]. This feature is increasingly common with growing emphasis on sustainable cities.

If the building envelope is largely planar, acoustic energy is reflected in a specular manner. This is a common feature in modern and contemporary architecture albeit undesirable in high-density cities [172]. To minimize environmental noise, it is crucial to promote diffuse reflections rather than specular reflections. The most direct approach is to design building envelopes with protrusions and textured profiles without adversely affecting the exterior aesthetics [172,175,181]. Although unlikely in high-density cities, another approach is to provide sufficient space between buildings for reduced sound reflections [182].

Focusing on a residential area that consists of only detached and semi-detached houses, Qu and Kang [183] found that the length and orientation of the houses could influence low-frequency noise at 50 Hz. Among the simulated scenarios, the best outcome revealed a maximum noise reduction of 3.3 dB. Although the noise source was a wind turbine, the results may suggest the potential influence of urban morphology on aircraft noise—also has a low-frequency acoustic signature—and motivate further research. At this point in time, it remains inconclusive whether changes made to urban morphology are truly beneficial in minimizing aircraft noise.

5.3. Concluding Remarks

This section has presented the background of the Balanced Approach in managing aircraft noise and how open windows and morphology of housing estates may be viable as additional options to consider. Instead of minimizing aircraft noise through policy proposals, urban planning professionals may consider these additional options from the outset of any residential site development.

On open windows, this section has shown that passive and active concepts are potentially suitable for aircraft noise reduction albeit further work is required for performance optimization. Even though promising outcome has been demonstrated in open windows incorporated with ANC system, some researchers [164,184] remain skeptical about the concept, arguing that it may be impractical for application in housing estates especially over a prolong period of time under different weather conditions. Considering the interior design of modern apartments, residents may not be attracted to the concept due to poor aesthetics, not to mention the need for additional circuitry and maintenance. Passive concepts may still be preferred since they are aesthetically comparable to conventional windows and are almost maintenance-free.

On urban morphology, this section has highlighted the scarcity of studies associated with aircraft noise. Only three studies were reported over the last 18 years (2002–2020). As such, an attempt was made to discuss relevant findings associated with traffic noise and wind turbine noise that may motivate further research that focuses on aircraft noise. At this point in time, conclusive evidence remains lacking to establish any influence of urban morphology on aircraft noise.

Considering the state-of-the-art in the various noise control measures discussed in this section, the most viable and reliable option at present may be passive concepts of open windows. Investment in research effort should be lesser than those of the remaining options (i.e., active concepts of open windows and urban morphology).

6. Conclusion

Owing to the COVID-19 pandemic, residents have been staying at home to work in the daytime, causing them to become more aware of aircraft noise that had been present before the pandemic. This article has first established how aircraft noise can be quantified to assess environmental impact via two types of noise metrics—single event and cumulative. Subsequently, this article has discussed how chronic aircraft noise exposure may cause direct and indirect health problems in residents. The former includes noise-induced hearing loss, annoyance, and sleep disturbance. The latter includes cardiovascular disease and cognitive impairment in children. Property value may also be negatively affected. These issues justify why it is timely to place more emphasis on the prediction and management of aircraft noise from the outset of urban planning, anticipating that work-from-home arrangement will likely be a norm of workplace management amid COVID-19 endemic.

Between the two categories of aircraft noise prediction models, this article has suggested why best practice models are more suitable for urban planning professionals compared to scientific models. This suggestion is based on the need for aircraft noise predictions to be performed in a straightforward manner so that they can quickly sense any potential aircraft noise issue in the built environment. Consequently, urban planning professionals may incorporate potential concepts in housing estates offered by the state-of-the-art in aircraft noise control measures to minimize noise exposure among the residents. At present, passive concepts of open windows may be the most suitable and reliable option to consider.

To conclude, anticipating the adoption of hybrid work arrangement moving forward, urban planning professionals may apply the concept put forth in this article as an avenue to understand how aircraft noise can negatively affect the built environment, which, in turn, justify why prediction and management of aircraft noise should be emphasized from the outset of urban planning. Consequently, less noise complaints are expected from new residents, leading to better quality of life.

CRediT Authorship Contribution Statement

Linus Yinn Leng Ang: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization, Project administration. Fangsen Cui: Resources, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors declare that this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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