JOURNAL OF ENGINEERING RESEARCH & SCIENCES

JENRS

www.jenrs.com
ISSN: 2831-4085

Volume 3 Issue 1
January 2024

Editorial

In this issue of our journal, we delve into a diverse array of topics spanning engineering, environmental science, hospitality, and conservation biology. Each paper sheds light on unique challenges faced within its respective domain, while also presenting innovative solutions and avenues for future exploration.

The investigation by the author into the reliability issues encountered in land grid array (LGA) packages underscores the critical importance of substrate integrity in high-frequency applications. Through a meticulous analysis, the researchers uncovered the role of moisture penetration in causing electrical malfunction, highlighting the need for advanced testing methodologies to mitigate such failures. This study not only contributes to the advancement of integrated circuit design but also underscores the significance of substrate material selection in ensuring package reliability [1].

Meanwhile, the proposal presented by for a Baggage Cart with Weighing Mechanism addresses a common pain point in the hospitality industry. By integrating a weighing mechanism into baggage carts, the proposed solution streamlines the process of weighing baggage for travellers, enhancing guest experience and operational efficiency. This innovative approach exemplifies the intersection of technology and service design, offering practical solutions to real-world challenges faced by both travellers and hotel staff [2].

The plight of the Australian lungfish, Neoceratodus forsteri, is brought to attention by, highlighting the profound impact of environmental changes on species survival. Human activities such as water usage and habitat alteration have threatened the survival of this iconic species, necessitating urgent conservation efforts. This paper serves as a stark reminder of the interconnectedness between human actions and biodiversity loss, underscoring the need for sustainable water management practices and habitat conservation initiatives [3].

Lastly, the systematic review by explores the transformative potential of Building Information Modelling (BIM) in construction risk management. By synthesizing key techniques and findings, the paper offers insights into how BIM can streamline risk identification, analysis, response planning, and monitoring across the project lifecycle. Despite the promise of BIM, challenges such as change resistance and model reliability remain significant hurdles to its widespread adoption, calling for concerted efforts to address these barriers [4].

Collectively, the papers featured in this issue exemplify the spirit of innovation and inquiry driving progress in various fields. From semiconductor reliability testing to sustainable construction practices, each study offers valuable insights and solutions to complex challenges. As editors, we are proud to present these contributions and look forward to seeing the impact they will have on their respective disciplines.

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Editor-in-chief

Prof. Paul Andrew

JOURNAL OF ENGINEERING RESEARCH AND SCIENCES

Volume 3 Issue 1 **January 2024**

CONTENTS

Received: 25 September, 2023, Revised: 10 January, 2024, Accepted: 10 January, 2024, Online: 30 January, 2024

DOI: https://doi.org/10.55708/js0301001

Application of deuterium Oxide (D_2O) Isotope Tracing Technique for Land Grid Array Package Failure Analysis

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ABSTRACT: A land grid array (LGA) is an integrated circuit design with a grid of contacts connected to other components of a printed circuit board. LGA is used for various high-speed and high-frequency applications due to its small terminal parasitic inductance. However, LGA packages are non-hermetic, as most the components of the LGA, like epoxy molding compounds, substrates, and resins are not airtight. These components can absorb moisture from working environment, and the moisture penetration will give rise to package reliability problems. In this study, a batch of LGA packages encountered electrical malfunction after Highly Accelerated Stress Tests (HAST) 85°C/85%RH reliability test 96 hours. The failure mode was causing the connected display panels showing white dots, as the LGA were used to control the external display panels. Although hot spot testing through thermal imaging was performed, it could not locate the failure point of the die. Traditional non-destructive tests, like X-ray inspection and Scanning Acoustic Microscopy techniques were also performed, but they could not detect any defect of the package which may be contributed to their detection limit. It is suspected that penetration of moisture into the LGA package caused electrical failure, however there is no direct proof to demonstrate this presumption. To solve above challenges, this work employed a new deuterium oxide (D_2O) isotope tracing method. Both good and bad LGA packages were loaded in the HAST chamber in which normal water (H_2O) was fully replaced with heavy water (D_2O). Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) was utilized to detected the D signal in the LGA package. By comparison, it was found that the moisture penetration through the via-resin interface of the bad sample was much faster than that of the good sample. Verification test was performed to replace the bad batch substrate (where moisture penetrated fast), and the new samples all passed the HAST test. It is confirmed that it is the via-resin interface in the substrate of the bad samples causing moisture penetration.

KEYWORDS: Land grid array (LGA) package, Deuterium oxide (D_2O), Isotope tracing, HAST, moisture penetration

1. Introduction

A land grid array (LGA) is an integrated circuit design with a grid of contacts connected to other components of a printed circuit board. LGA is used for various high-speed and high-frequency application due to its small terminal parasitic inductance. However, LGA packages are non-hermetic, as most the components of the LGA, like epoxy molding compounds, substrates, resins are not airtight. These components can absorb moisture from working environment, and the moisture penetration will give rise to package reliability problems.

In this study, there are 2 batches of LGA packages from 2 different suppliers, called Batch A and Batch B. Batch A packages all passed the Highly Accelerated Stress Tests (HAST) 85°C/85%RH reliability test 96 hours. While Batch B packages encountered 100% electrical malfunction after HAST 96 hours. The failure mode was causing the connected display panels showing white dots, as the packages were used to control the external display panels.

Although hot spot testing through thermal imaging was performed on the bad samples, it could not locate the failure point of the die. Traditional non-destructive tests, like X-ray inspection and Scanning Acoustic Microscopy techniques were also performed, but they could not detect any defect of the package which may be contributed to their detection limit. It is suspected that penetration of moisture into the LGA package caused electrical failure, however there is no direct evidence to find out the moisture penetration path.

To solve above challenges, this work employed a new deuterium oxide (D_2O) isotope tracing method. In D_2O, deuterium (D) is a stable hydrogen (H) isotope whose nucleus consists of one proton and one neutron. In nature the D-to-H (D/H) ratio is about 1.55 x 10-4 [1]. In this work, both Batch A good samples and Batch B bad samples were loaded in the HAST chamber in which normal water (H_2O) was fully replaced with heavy water (D_2O). During the HAST process, the D_2O moisture will penetrate the packages through the non-hermetic packaging materials or their interfaces. After that, the samples were discharged from HAST chamber, and the presence of D in the samples were detected by Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS).

The results showed that moisture penetration through the via-resin interface of the bad sample was much faster than that of the good sample. It is obvious that moisture penetration through the via-resin interface caused moisture-induced failure. Verification test was performed to replace the bad batch substrates (where the vias locate), and all the improved samples passed the HAST test. It is confirmed that it is the via-resin interface in the substrate of the bad samples causing moisture penetration. The data showed that deuterium D_2O isotope tracing method is a useful means to detect the moisture penetration path.

2. Experimental

The LGA package (model 6193) studied in this work is shown in Figure 1. The dimension of this package is 14099 x 2317 x 1312 μm (length x wide x thickness). In this study, there are 2 batches of LGA packages from 2 different suppliers (Batch A and Batch B). Batch A packages all passed the HAST 85°C/85%RH reliability test 96 hours. While Batch B packages encountered 100% electrical malfunction after HAST 96 hours.

Heavy water method was used to detect the moisture penetration paths in this LGA package. The experiment included below steps, which are illustrated in Figure 2 [2].

1) Sample treated with D_2O: The samples were loaded into the HAST chamber with condition of 85°C/85%RH for 1 hour. In the HAST run, H2O was fully replaced by D_2O in the chamber. The purpose is to let D2O moisture permeate into the package through the invasion paths.

2) Sample cross-section: The samples were discharged from the HAST chamber, followed by cross-section to expose the possible moisture invasion paths.

3) TOF-SIMS analysis: The samples were analysed by TOF-SIMS to detect the presence of D in the good and bad samples. ToF-SIMS model is ION-TOF SIMS 5 with Primary Ion 133Cs+.

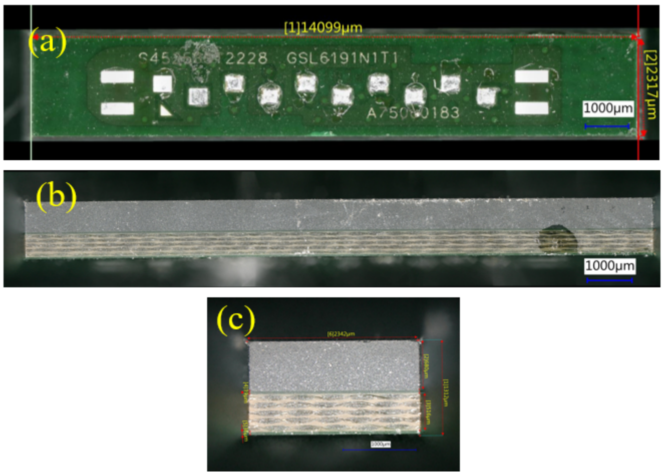

Figure 1: Land grid array package device used in this study (a) bottom view, (b) long side view, and (c) short side view.

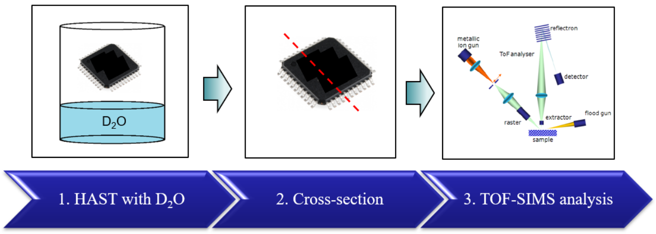

Figure 2: D2O isotope tracing test flow [2].

3. Results and Discussion

Figure 3a. shows the cross-section and optical image of the LGA sample with dimension measurement. Both Batch A and Batch B are with the same structure. From the structure, it is suggested there are 3 most possible moisture invasion paths to the die. These 3 paths are discussed as below (see Figure 3b).

- Path 1: The die is covered by the epoxy molding compound, which is a non-hermetic material. Therefore, moisture can permeate directly through the molding compound from the top to the die (see the red arrow in Figure 3b).
- Path 2: There are copper (Cu) vias embedded in the substrate under the die. The vias are filled with resin (model PHP-900 IR-6P). As the resin is a non-hermetic material, it is also a moisture invasion path. Moisture could penetrate from the substrate bottom to the die through the via resin (see the yellow arrow in Figure 3b).

- Path3: Moisture can penetrate through the substrate to the die where there is no Cu layer (see the white arrow in Figure 3b).

There are also other moisture penetration paths to the die. However, from this LGA structure, these 3 paths should be the fastest penetration paths suggested by the authors.

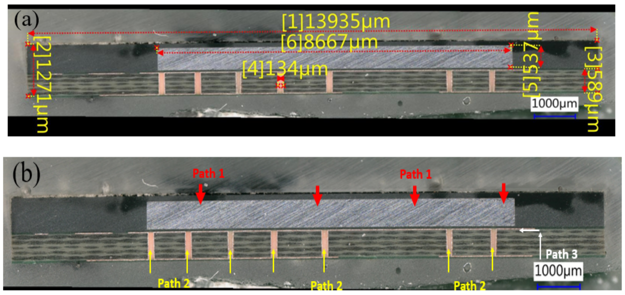

Figure 3: Cross-section and optical image of the LGA, (a) with dimension measurement; and (b) with illustration of 3 most possible moisture penetration paths.

TOF-SIMS surface scanning was performed at both Batch A good samples and Batch B bad samples. Figure 4 shows the TOF-SIMS surface scanning areas and results of the path 1, i.e., epoxy molding compound above the die.

Figure 4a presents the TOF-SIMS surface scanning areas of path 1 in the good sample, called area OK-1. The scanning area is 200μm x 200μm. D ion mapping result of OK-1 was showed in Figure 4b. For easy observation the D concentration, the D ion mapping was converted to intensity profile from surface of the molding compound to the die (see Figure 4c). It can be observed that weak D signal in OK-1 area. Same TOF-SIMS surface scanning areas was performed on the path 1 in the bad sample, called area NG-1 (see Figure 4d). D ion mapping of areas NG-1 was presented in Figure 4e, and D ion intensity profile from surface of the molding compound to the die was presented in Figure 4f. Compared the D ion intensity of the OK-1 and NG-1, there is no obvious difference. Weak D signal was observed for both areas.

The via-resin areas (path 2) were analysed for both OK and NG samples for comparison purpose. Figure 5a shows the TOF-SIMS surface scanning area at the good sample via (area OK-2). The scanning area is 1000μm x 500μm. Figure 5b shows the D ion mapping of area OK-2. The D ion mapping was converted to intensity profile from left to the right side of the via as shown in Figure 5c. In Figure 5c, it is showed that there is a strong sharp peak at the resin center, which indicates that D_2O penetrated through the resin. It is noted that there are small peaks at both sides of the centre peak. It is suggested that moisture penetrated through the interface between the resin and Cu, which contributed to the small peaks.

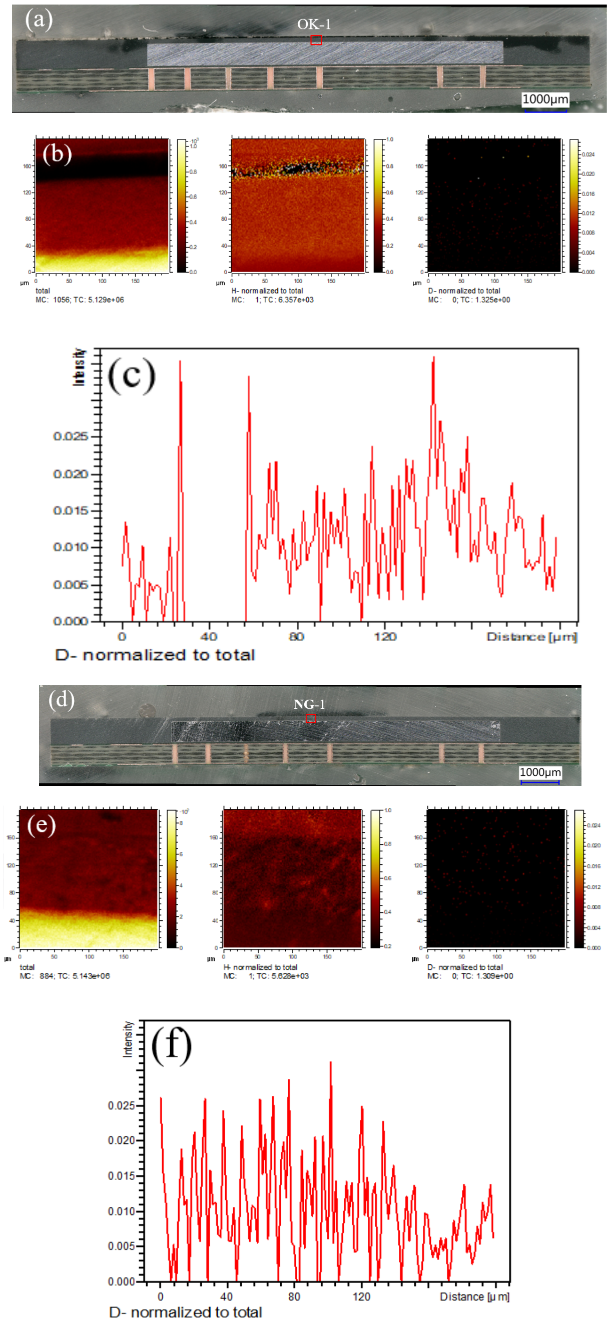

Figure 4: (a) TOF-SIMS scanning areas at the molding compound location of OK sample; (b) H and D ion images at area OK-1; (c) D ion intensity profile at area OK-1; (d) TOF-SIMS scanning areas at the molding compound location of NG sample; (e) H and D ion images at area NG-1, and (f) D ion intensity profile at area NG-1.

Same analysis was performed on the bad sample (see Figure 5d-5f). Figure 5d shows the ToF-SIMS surface scanning area of the via in the bad samples, called area NG-2. The D ion mapping is showed in Figure 5e. Figure 5f presents the D intensity profile from left to the right side of the via. In Figure 5c, it is showed that there are 2 strong sharp peaks at the via-resin interface. However, the D intensity of the resin center is much lower. It indicates that in the bad sample, moisture penetration was mainly by the via-resin interface.

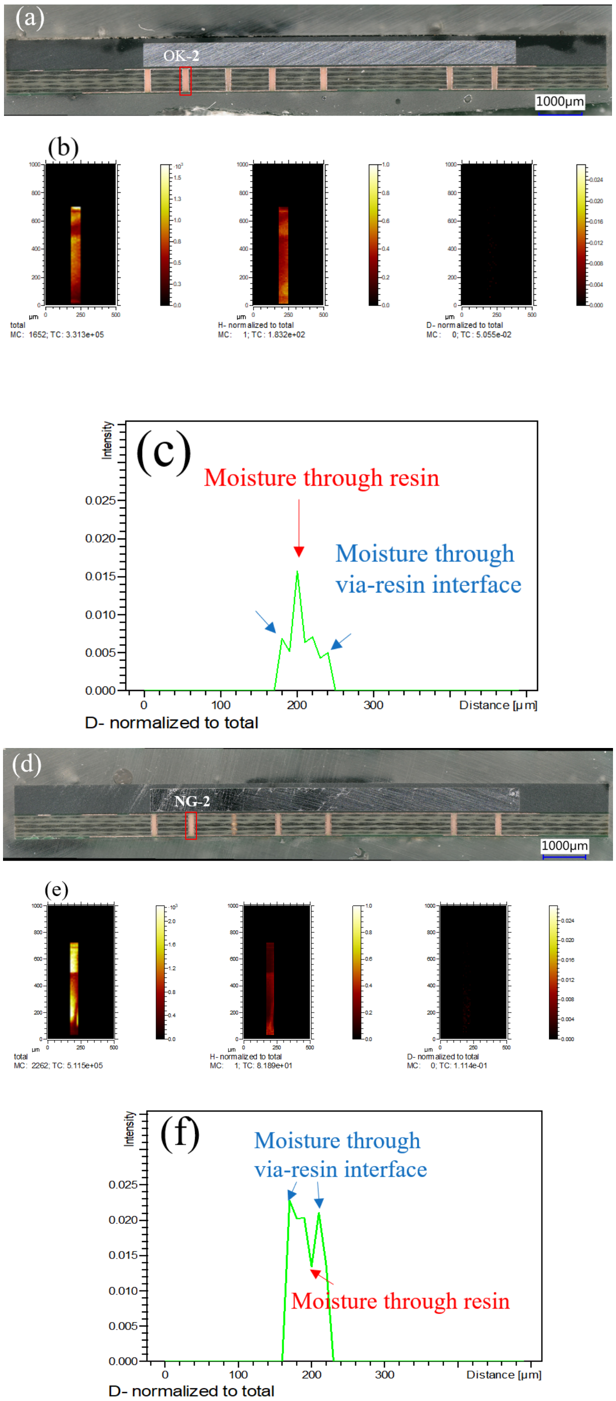

Figure 5: (a) TOF-SIMS scanning areas at the via location of OK sample; (b) H and D ion images at area OK-2; (c) D ion intensity profile at area OK-2; (d) TOF-SIMS scanning areas at via location of NG sample; (e) H and D ion images at area NG-2, and (f) D ion intensity profile at area NG-2.

For easy comparison of the OK and NG sample, Figure 6 compared the D signal in the via between these 2 samples. It is obvious that moisture penetration ways are totally different between these 2 samples. In the OK sample, moisture penetrated mainly by the resin (see Figure 6a). Whilst, in the NG sample, moisture penetrated mainly by the via-resin interface (see Figure 6b). It is also noted that D intensity of the NG samples is much stronger than that of the OK sample, indicating more moisture penetration. The next question is why the moisture penetration path and intensity of the OK and NG samples are different? It is suggested that the interfacial adhesion of via-resin of the NG sample is weak which allows easy moisture penetration. SEM characterization was performed to characterize the OK an NG vias (see Figure 6c and 6d). However, there is no obvious gap or delamination of the via-resin interface of the NG sample, neither the OK sample. It is suggested that because the molecular diameter of water molecules (H_2O) is about 2.75 angstrom, which is much smaller than that of the resolution of SEM.

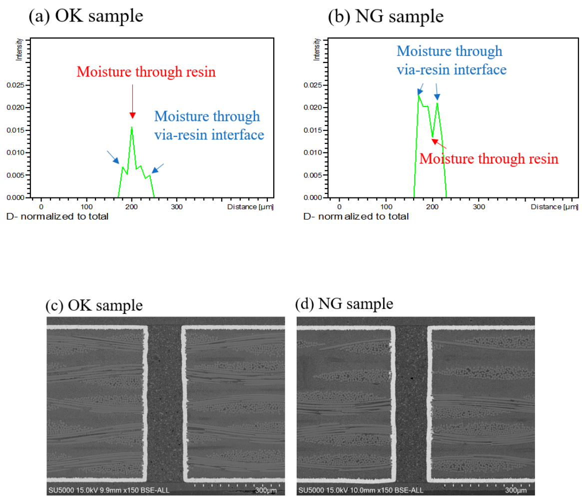

Figure 6: D ion intensity profile at the via area of (a) OK sample vs. (b) NG sample; SEM image of the via area of (c) OK sample vs. (d) NG sample.

As discussed in previous section, another possible moisture penetration path is through the substrate to the die where there is no Cu layer to block the moisture penetration (Path 3). Figure 7. shows the ToF-SIMS surface scanning on the path 3 areas of both OK and NG samples. Figure 7a-7c shows the OK sample ToF-SIMS scanning area and D data, and Figure 7d-7f shows the NG sample data, respectively. Figure 7c and 7f show the D ion intensity profile from substrate bottom to the top. By comparison Figure 7c and 7f, weak D signal was detected at Path 3 areas for both samples, but there was no obvious different between these 2 samples. So, it is suggested that moisture penetration through Path 3 was weak and was not contributed to the sample failure.

By comparing the moisture penetration data of the 3 paths, i.e., Path 1, 2 and 3, it could be found that both OK and NG sample moisture penetration results of path 1 and 3 are similar (see Figure 4 and Figure 7). The difference is at the Path 2 (see Figure 6). For the NG sample, moisture penetrated through the via-resin interface is much stronger than that of the OK sample. It is suggested that moisture penetration through the via-resin interface contributed to the sample electrical failure, even though no obvious gap at the via-resin interface was observed by SEM. Further verification study was performed to prove the D2O isotope tracing data. In the verification study, the bad batch substrate (where moisture penetrated fast) were replaced by another supplier (Supplier A). In the subsequent HAST, all the new samples passed the HAST test. The HAST results is presented in Table 1. It is confirmed that it is the via-resin interface in the substrate of the bad samples causing moisture penetration. The verification result aligned with what the D_2O isotope analysis found.

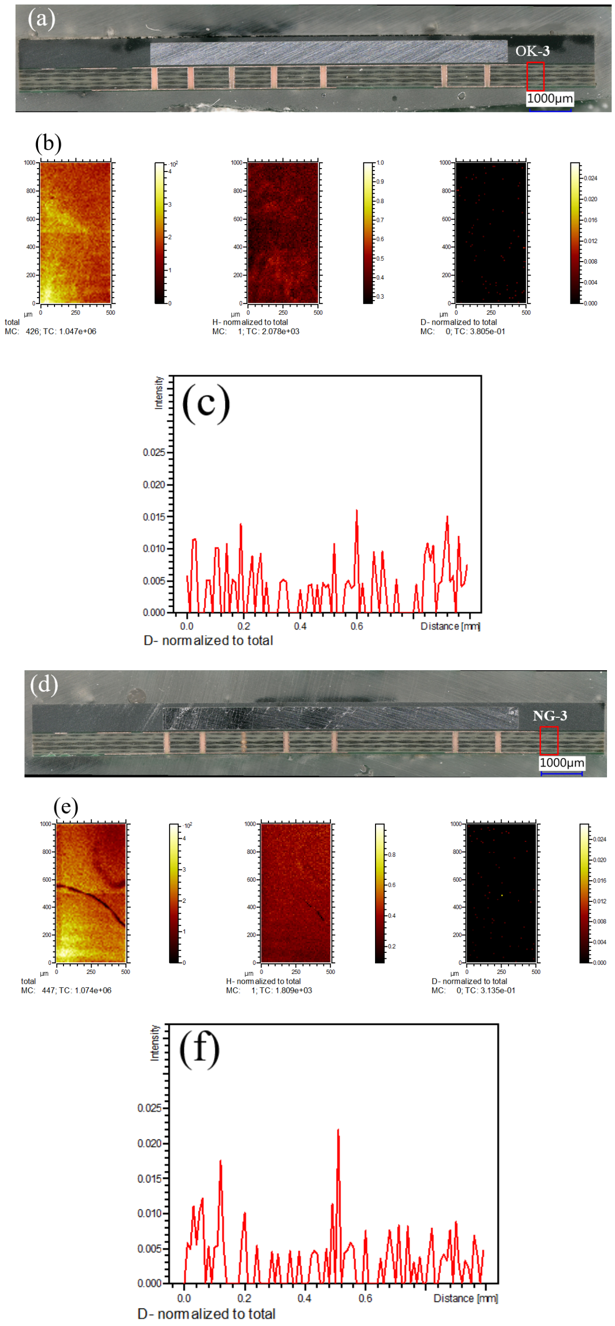

Figure 7: (a) TOF-SIMS scanning areas at the substrate location of OK sample; (b) Total, H, and D ion images at area OK-3; (c) D ion intensity profile at area OK-3; (d) TOF-SIMS scanning areas at substrate location of NG sample; (e) Total, H and D ion images at area NG-3, and (f) D ion intensity profile at area NG-3.

Table 1: HAST results

Batch	HAST results
Batch A	100% passed
Batch B	100% failed
Improved Batch B (Substrate replacement)	100% passed

4. Conclusions

In this study, application of deuterium oxide isotope tracing technique was employed for polymer land grid array package failure analysis. The failed sample after D_2O moisture treatment was analysed using TOF-SIMS. The results showed that there was a distinct high peak of D ion at the via-resin interface of the NG sample, indicating obvious moisture penetration. Whilst, the D ion at the OK sample was mainly at the resin itself and was much weaker than that of the NG sample. Verification test was performed to replace the bad batch substrate (where moisture penetrated fast), and the new samples all passed the HAST test. It was confirmed that it was the via-resin interface in the substrate of the bad samples causing moisture penetration. This D result was obvious evidence to show the electrical failure of the bad samples was contributed to the moisture concentration through the via-resin interface.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgment

The authors would like to acknowledge the support from Wintech-nano and Silead.

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Received: 04 October, 2023, Revised: 06 January, 2024, Accepted: 06 January, 2024, Online: 30 January, 2024

DOI: https://doi.org/10.55708/js0301002

Baggage Cart with Weighing Mechanism for Hotels and Airlines

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ABSTRACT: In this article, it has been proposed a functional design of Baggage Cart with Weighing Mechanism for Hospitality Industry based on empirical observations. This design is expected to promote and become one of the high demand products which can later be used especially by hotels and respective airlines. It has been often observed that travelers are always concerned about the maximum weight of their baggage allowed in order to board a flight. Because as per norms of airlines one needs to carry a specific amount of baggage in the flight, in case of extra weighed baggage carried by a guest, he/she is charged extra amount as per KG by the respective airline. Keeping this point in mind, travelers are always conscious about the weight of their baggage before boarding a flight to avoid the last-minute hassle of paying huge extra money, and sometimes they need to drop the necessary items out from the baggage to adjust the weight of the baggage. In hotels, a guest request to weigh his/ her luggage is dealt with in the following ways: The front office associate/porter first needs to fetch the baggage from the guest room and bring it up to the bell desk or need to drag it up till time office / receiving area where it is weighed on a heavy-duty weighing scale. It is the traditional way of measuring baggage. The traditional way is time-consuming, uncomfortable, and less suitable to support the need of the traveler. Hence, to minimize the time and efforts, we wanted to invent a mechanism that will help and reduce the burden of managing the separate weighing machine, and therefore we came up with a baggage cart with a weighing mechanism in it.

KEYWORDS: Baggage Cart, Weighing Mechanism, Customer Satisfaction, Service Quality

1. Introduction

Passenger Satisfaction is a crucial metric in order to evaluate airport performance. International airports in various regions or countries usually do not compete with each other. Passengers generally do not have the choice to choose between airports, irrespective of the quality and price of airport services. However, Passenger's demand for airport services is likely to be fairly inflexible [1]. To minimize time, effort, and ease out the task, the design provides a mechanism to weigh the baggage as per the guest's request. While working in the hotel industry, it was a routine task to deal with guests and their needs and out of all to weigh their baggage was one of them. One genuine problem which is paid less attention and provided with an ordinary, less effective, or non-hospitable solution is the handling of a traveler's need of weighing his baggage. Moreover, Airports' key customers are passengers and their initial impressions of airport facilities and services can significantly impact their perceptions and evaluations of the airport. Therefore, it is vital for the airports to provide safe, comfortable and convenient services in a cost-effective manner [2]. Transactions involving goods and services are not the only aspects of business. Its capacity to last is significantly reliant on a variety of humanitarian aspects related to the management and upkeep of commercial relationships with clients, suppliers, and staff, particularly when conducting business internationally [3]. Keeping these in mind, Quality of Service as apparent by customers is a comparison amongst performance and expectations [4]. As per [5], The overall observation of service quality is determined by the modification between customers' expectations and their actual experiences. When a customer's experience matches their expectation, service quality is perceived as upright. In other words, Quality of the service is measured by comparing customer expectations with their experiences and this comparison is based on the performance of service delivery. The goal of providing better service to clients is to meet their needs in addition to making sure they are completely satisfied with the service they are utilizing [6]. In the hospitality industry, it is a routine task to weigh the baggage of guests. The proposed design provides a mechanism to weigh the baggage as per the guest's request with minimal time, effort. Present solutions are not convenient and need the efforts of the porter to fetch the baggage to and fro between the guests' rooms and hotel utilities which is a time-consuming process.

2. Technical Background

At present, the hospitality industry is using the following mechanisms to weigh the baggage. Based on empirical observations and as shown in Figure 1 below, Earlier In a traditional way, a porter needs to fetch the bag from the guest room which is taken to the time office / receiving area where it is weighed on a heavy-duty weighing scale. The moment it's being measured, it is properly tagged and delivered to the respective guest room. The process needs to be executed immediately on the guest's demand as the guest has to check out and take a flight or train. Even a reasonable delay in the process upsets the guests and creates a bad impression of the hotel.

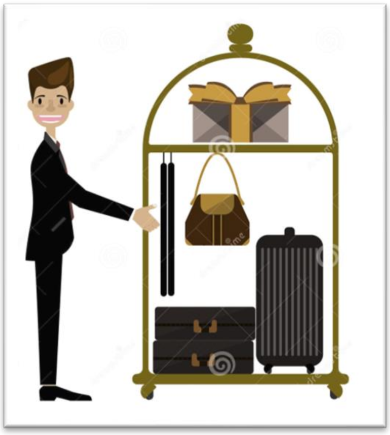

Figure 1: Traditional way of Measuring Baggage through the help of Porter

In another mechanism, as per empirical observations and as shown in Figures 2 & 3 below, some hotels use a weighing device with a lifting hook. The porter has to hold the device and lift the bag hooked to the device to weigh it. Sometimes the process may result in a muscular sprain in the porter's hand or back or lead to dropping the bag, which could again lead to a bad impression of the hotel.

In a few hotels, as per empirical observations and as shown in Figure 4 below, the guest is prompted to measure his / her baggage on his own by using the weighing scale kept in their bathroom. However, this system is not suitable as it is meant for weighing human body weight. In case one holds a bag and stands on the machine, it gives total weight which is not an appropriate method. it's not even feasible to keep a large piece of baggage on the surface of a weighing scale.

Figure 2: Traditional way of Measuring Baggage through a weighing device with a lifting hook (top view)

Figure 3: Traditional way of Measuring Baggage through a weighing device with a lifting hook (front view)

Figure 4: Traditional way of Measuring Baggage through the weighing scale kept in their bathroom

3. Related Work

3.1. Prior Art

As per empirical observations, figure 5 represents the traditional way of measuring the baggage. It would be easy and convenient for the front office associate/porter to use efficient ways to reduce their efforts and save time.

As per empirical observations, the use of the proposed mechanism in baggage cart is not restricted or limited to just hotels only, even the respective airlines can use it during a passenger's arrival inside the airport, before

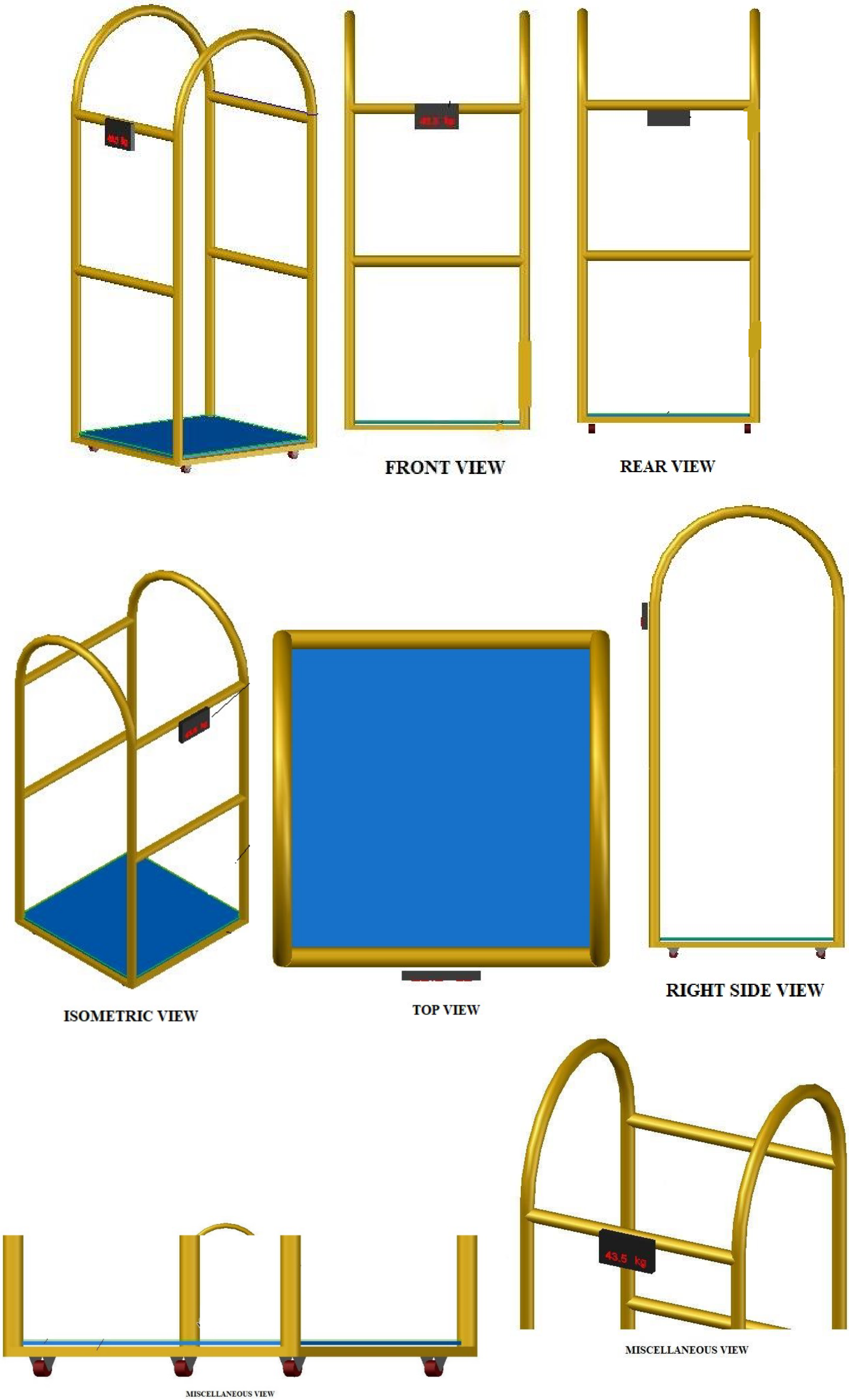

Figure 6: Proposed design for Baggage Cart with Weighing Mechanism for Hotels and Airlines

moving towards their flight one needs to finish check-in formalities including the weighing of their bags. Using this mechanism would enable them to get the results faster than the existing ones.

Figure 5: Traditional way of Measuring Baggage through the weighing scale

3.2. Advantage of the proposed system in comparison with prior art

- **Time Effective:** It saves time as it is always available with Front Office / Bell Desk.
- **Easy Handling:** It is always handy and in use by Bell Desk Staff.
- **Reduced Efforts:** No more to-and-fro efforts, as a handy baggage cart with a weighing mechanism, is available all the time.

3.3. Proposed Solution

The mechanism was designed to minimize the time and effort required in the traditional weighing method through a separate weighing machine. The proposed design allows installing the weighing mechanism on the baggage cart. The proposed design for Baggage Cart with weighing mechanism for hotels and airlines are shown in figure 6.

4. Hardware Implementation

As per empirical observations, the surface of the baggage cart has a mechanism to measure the weight. Upon placing a bag on the cart's surface, it will display the weight on the digital display mounted on the cart. The baggage cart will appear like a regular baggage cart when the digital meter is turned off.

5. Conclusions

The product is designed to eliminate the existing flaws used by respective hotels and airlines of guests for weighing their luggage, especially at the eleventh hour of checking out of the hotel. As per the enclosed pictures from 1-4, traditionally these are the methods of fetching baggage and measuring them too which are not at all convenient and time-effective. The most significant advantage of the baggage cart with a weighing mechanism is that it can be used by both hotels and airlines for their purposes. This product is expected to find high acceptance by hospitality professionals because of lesser effort, easy handling, and being time effective.

Conflict of Interest

The authors declare no conflict of interest.

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Received: 11 October, 2023, Revised: 10 December, 2023, Accepted: 10 December, 2023, Online: 30 January, 2024

DOI: https://doi.org/10.55708/js0301003

Four Rivers and a Reservoir – the Last Homes of the Wild Australian Lungfish

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ABSTRACT: The environment of the Australian lungfish, *Neoceratodus forsteri*, in south east Queensland, has changed fundamentally since white settlement, and this threatens the survival of the species. Some of the damage to lungfish habitats is the result of human determination to use water for the various needs of industry and people. Additional problems include droughts and floods, as well as loss of plant or animal biodiversity of value to basal fishes like lungfish. Submerged aquatic plants used by lungfish as spawning sites and refuges for the young have been significantly reduced, and food animals for adults and hatchlings are absent or much less common. Without appropriate nutrition for adults, eggs lack the right nutrients for young lungfish. They are unable to develop properly, and die at an early age. Populations of the Australian lungfish in south east Queensland are no longer reproducing sufficiently to guarantee survival of the species in wild habitats of south east Queensland. Lungfish have already died out in Enoggera Reservoir, one of the localities to which lungfish were introduced in 1896. Lungfish will soon be extinct in the four remaining rivers to which they are endemic, because so much biodiversity has been lost. They may survive for a while in the protected environments of zoological parks and aquaria, but not in the habitats where they evolved and lived for so long.

KEYWORDS: Endangered, Extinction

1. Introduction

Lungfish first appeared in the Devonian, and have been found in fossil deposits in many continents and in most epochs since then. Two major families of lungfish are still living, although all of the other lungfish groups are extinct. The Australian lungfish, *Neoceratodus forsteri*, belongs to the Neoceratodontidae, that first split away from the Lepidosirenidae, with four species in Africa and one in South America, in the early Triassic [1]. The group that includes *N. forsteri* colonised many environments in central and eastern Australia in the past [2]. Most of these species, from Tertiary deposits in Australia, are now extinct, except for *N. forsteri*, surviving in coastal rivers that are much affected by water impoundments, in southeast Queensland. This contribution discusses the plight of the last remaining populations of *N. forsteri*.

The Australian lungfish has lived through many changes to its habitat since it became known to scientists in 1870 [3]. The species has faced droughts and floods, and significant interference from humans, such as habitat loss, reduction in biodiversity in rivers, and the building of water impoundments. Initially, lungfish were considered to be found only in the Mary and Burnett Rivers [4], but recent research has shown that lungfish are endemic to the Brisbane River and possibly also the Pine River as well as the Mary and Burnett Rivers [5]. That *N. forsteri* is endemic to the Brisbane River has now been accepted by other lungfish researchers [6], although their evidence for this statement is unfortunately based on an incorrect assignment of a fossil lungfish found in a well in the estuary of the Brisbane River [2]. One of the early translocations of lungfish in 1896 placed them in an isolated water impoundment, known as Enoggera Reservoir. They have now died out in this habitat.

Adult lungfish are present, and still numerous, in most environments, although eggs and hatchlings are vulnerable and face many hazards. Apart from accidental catches by fishermen, and human interference with their habitat, the only real threats that may affect adult lungfish in a natural environment are reduced food supplies and old age. Unfortunately, the situation faced by young lungfish is very different. They require refuge from numerous predators in the environment, as well as shelters and food supplies, all now absent from most habitats where lungfish live.

Lungfish are now seriously endangered in all of their wild environments. Recruitment has failed in many habitats. Reasons involve the loss of biodiversity in the rivers and reservoirs, lack of suitable food, and damaged spawning sites. Spawning has ceased in many environments. Rivers are either wrecked by drought or flooding or have been turned into reservoirs. Even if the lungfish manage to spawn, lack of appropriate nutrition for the parents means that eggs and embryos are not properly provisioned and all of the young are affected by deficiencies in the biochemical components of the eggs laid down by the parents [7–9]. The effects of these changes are already catastrophic.

2. Methods

Data on the distribution of lungfish in their current habitats of isolated coastal rivers was derived from literature. Electrofishing to assess the size of the adult population of lungfish was not done, because the main issue facing the species is lack of food and problems with spawning and recruitment. Adult lungfish are still common in parts of the rivers, but young lungfish are absent. Information on the difficulties faced by lungfish in their current environments came from field observations over many years of research, with some published information.

3. Results

3.1. The Burnett River

The Burnett River system, the largest of the coastal rivers that are home to lungfish, extends over a wide area of southeast Queensland (Fig. 1). The river rises near Mount Gaeta in the foothills of the Great Dividing Range and joins the sea in Hervey Bay near Fraser Island. Originally surrounded by forests, the Burnett River catchment is now home to numerous sugar cane farms and other agricultural activities.

The river has many tributaries, most now blocked by reservoirs, built since the 1960's, and some, such as the Ned Churchward Weir and Paradise Dam on the main river, more recently. The most famous of the tributaries is Auburn, the ancestral home of the Australian lungfish [3], now notable for a small national park near a waterfall. The Auburn is well into the hinterland, a long way from the coast. Lungfish are no longer present in this part of the Auburn River, and they are, in effect, extinct in their type locality. The lungfish is now confined to the main river and short regions of major tributaries [10].

Scientists are often the last to take note of new animals, and this is certainly true of the Australian lungfish. The fish were always well known to Aborigines, and later to early settlers. Both of these groups used them for food. There is one record from 1842, describing a story told by a "wild white man" who escaped from a penal settlement in 1829 and lived for many years with a tribe of Aborigines [11]. They often ate lungfish. The escaped convict, Jem Davies, was the first white person ever to see a lungfish.

The first scientific description of the lungfish appeared in a short article by Krefft in 1870 [3], using two preserved adult fish from the Auburn River. Eggs and embryos of the lungfish were not found for another fourteen years, and not described in any detail until a German naturalist, Richard Semon, came to the McCord property in Queensland in 1892 to collect and study the eggs and take numerous examples home to be examined by his colleagues in Europe [12]. Semon has the distinction of finding the first wild hatchling, one inch long, among submerged water plants in the river, the only wild hatchling to be discovered for many years. This gave rise to the frequently repeated comment that juvenile lungfish were rarely to be found, and the species was on the brink of extinction. For many years, this statement proved to be needlessly pessimistic. Although few wild juveniles have been recorded, lungfish have survived. Now, it could well be prophetic. Lungfish are in real trouble, because food supplies for adults and young are now reduced. A balanced system of long-lived adult fish, and low recruitment, operating for millennia, has been thrown out of equilibrium.

The Burnett River originally flowed more or less as nature intended, with numerous tributaries that united to form meandering rivers, having many long, deep pools and short stretches of rapid flow. The river was affected by floods, and in times of drought was reduced to "chains of waterholes", but fish and other animals retreated to the deep pools left behind, and colonized the river when it began to flow again. The water holes were extensive, and retained populations of plants and animals, including lungfish, throughout the drought. The river was affected by agricultural activities, and by towns and villages, and the occasional disaster when unwanted effluent from factories entered the river, but there were no major interruptions to the flow of the river. Plenty of habitats remained for the lungfish, throughout the whole system.

The early Burnett system is a far cry from the debased and altered river that exists now. The Burnett River now has 26 water impoundments, and many are impassable to lungfish. There are very few fishways on any of the water impoundments, and lungfish often ignore them when they are present [13, 14].

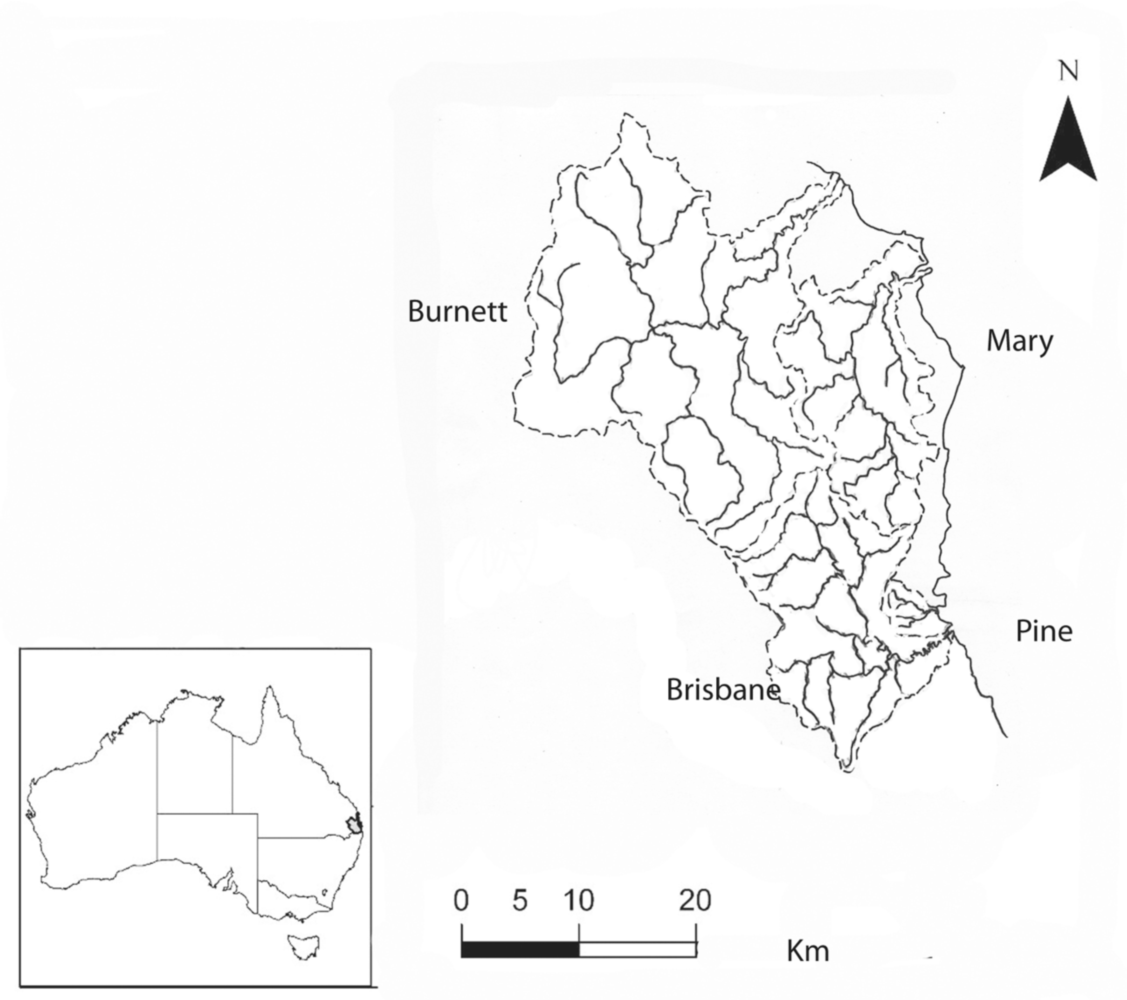

Figure 1: Coastal rivers in Queensland with an endemic population of lungfish. These rivers are isolated from each other by mountain ranges.

Caldwell was the first to find spawn of the lungfish, in a number of different sites in the Burnett River, assisted by Indigenous people, and the first to attempt to raise the eggs and embryos [15]. Caldwell does not list the numbers of viable versus dead eggs. In [16], the author was the first to raise lungfish to young juveniles, well beyond the tricky stages of egg and hatchling development, but he published little of his methods. He found eggs on *Vallisneria* plants. In [17], the author worked for many years, collecting eggs and attempting to raise them, often with little success because he failed to recognise that young lungfish are not filter feeders, and, until they reach a certain size, are incapable of breathing air because the lungs have not yet developed. He was much less successful than Illidge. In [17], the author considered that the weeds on which lungfish spawn are *Vallisneria*, *Hydrilla* and, if nothing else is there, *Nitella*. Espinoza and his colleagues [18] made collections of eggs but give little information on development and recruitment, or even how many eggs were actually healthy and viable.

Later studies by State Government officers have listed an enormous number of weeds on which eggs were found, and some records of juveniles and subadults [10]. Weeds used for spawning were species of *Vallisneria*, *Hydrilla*, *Nitella* and *Potamogeton*, as well as *Myriophyllum*, and even grass. They refer to the proportion of living eggs in the field, higher as macrophyte density increased. The number of macrophytes apparently used in certain years reflects eggs being shed loose into the water current, caught by any weed in the current and not specifically laid there during spawning. In those years when spawning was prolific, eggs were also found in rocky pools in the river, bereft of any plant cover. The work of these authors is now twenty years old and no further information has appeared [10].

3.2. Mary River

The Mary River, south of the Burnett River, rises at Booroobin, west of the town of Landsborough, and flows north to the Great Sandy Strait on the coast of Queensland (Fig. 1). Historically, the Mary River was a perfect environment for lungfish, with deep pools, plenty of submerged aquatic vegetation, fish and invertebrates, rainforests growing on the banks, and short stretches of shallow fast flowing water [19].

Gradually, the surrounding land was taken for farms, causing some changes, but the river was not otherwise much altered in historical times, except perhaps by cattle grazing on the banks. The Mary River was the source of four adult lungfish preserved and sent to London in 1870, where they formed the basis of a description by Gunther [4] in the following year.

The Mary River already has 11 major water impoundments, and the plan to turn the whole river into a long, shallow water impoundment, to be known as Traveston Dam, was rejected by the Federal Government. However, several tributaries of the Mary River have been turned into reservoirs, such as Borumba Dam over Yabba Creek, built in 1964. These water impoundments help to supply water to the Mary Valley residents, and support irrigation for farming.

A single collection of lungfish eggs and embryos was made in Imbil late in the season of 1976 [20]. Eggs were found among water plants in two or more feet of water. No data on the number of viable eggs was recorded. There are few additional records of spawning and egg collections in the Mary River, but, at times, large numbers of juvenile lungfish have been collected and measured [10]. Little information is available on survival of eggs and embryos from the Mary River.

3.3. Brisbane River

South of the Mary River, and separated from it by the mountains of the Conondale Ranges, is the Brisbane River system (Fig. 1). The Brisbane River rises in the foothills of the Great Dividing Range east of the town of Kingaroy, and joins the Stanley River, the largest tributary, which originates in the Conondale ranges. The Brisbane River is a large permanent system with many tributaries, some small and insignificant and others extensive, meandering across a wide area of mostly flat ground, starting in the mountains and discharging to the sea on the east coast. The Brisbane River is similar to the Mary River in fauna and flora, and in water composition, but much deeper and flowing faster in the unaltered reaches.

The early descriptions of the author are lyrical, presenting an idyllic picture [21]. After white settlers began to alter the river, for farming or habitation, this changed rapidly. The estuary of the river is affected by tidal flows, and by dredging, initially to allow for navigation and later, in 1862, to provide gravel for the building trade. This has made the river, for much of its length, murky and not particularly salubrious. Although dredging ceased many years ago, and navigation by large ships is now confined to the Port of Brisbane, the lower Brisbane River is still muddy. This does not apply to the upper reaches of the river, where the water was, and still is, clean and fresh.

Prior to 1895, when it was decided to move lungfish around the state, to ensure the survival of the species, there are no written records of lungfish in the Brisbane River. However, lungfish bones 3500 years old were found in an Aboriginal site, the Platypus Rockshelter, near Northbrook on the Brisbane River, a long way from the Mary River and from the Burnett River [5]. Lungfish are endemic in the Brisbane River.

Much of the Brisbane River flowed through open country with sparse eucalypt forest, often burnt by Aborigines to encourage new growth and attract herbivorous prey animals. Riparian vegetation at that time included many rainforest elements. Bottlebrush trees growing close to the river bank provided masses of fine rootlets suspended in the water where lungfish could lay their eggs and hatchlings could find food and hiding places. The entire system of riparian vegetation provided a shady and sheltered environment. This has now changed, and the Brisbane River catchment is affected by two large reservoirs, Lake Wivenhoe and Lake Somerset, with no fishways, taking up much of the original river. The oldest reservoir, Mount Crosby Weir, is small, and does have a fishway, which lungfish are too heavy to use.

The Brisbane River was originally a rich environment for aquatic animals. There were extensive beds of eelgrass in shallows and deep water at Northbrook, and at Fernvale, just below Twin Bridges, where small clams such as *Corbicula* lived. At Lowood a few kilometres upstream of Twin Bridges, there were snails such as *Thiara* living on rocks and among weeds as well as *Corbicula* in the shallows. In all areas, there were banks of water plants in deep water, as well as river bottlebrush growing along the edge of the river, with roots hanging into the water, home of *Corbicula*, rotifers, worms, small prawns, sponges, little fish, and a favourite site for lungfish to spawn [22]. This picture was repeated along the length of the river, outside the towns and villages.

Before Lake Wivenhoe was built, lungfish spawned in many sites along the river, mostly on the submerged rootlets of *Callistemon* trees growing on the river bank, or on the roots of *Lomandra* growing close to the *Callistemon* trees. In shallow areas, they laid eggs on the leaves of extensive beds of *Vallisneria*, and occasionally in banks of *Hydrilla* growing in deeper water. The most extensive sites were at Northbrook, close to the Platypus Rockshelter. The season in the River was long, beginning in in the middle of August and continuing until December. Mortalities of eggs collected from these sites were usually low, and most of the eggs collected were newly laid or only a few days old [22]. Food and refuges for hatchling lungfish were plentiful, among the tree rootlets or the *Vallisneria* plants. This safe and rich environment was destroyed for ever when Lake Wivenhoe was created, and decent spawning sites were only to be found in parts of the river remote from the reservoir. In places like Lowood and Fernvale, lungfish made use of the trailing roots of *Callistemon* trees, and sometimes of *Lomandra* plants on the river bank. They also used *Vallisneria* plants in the shallow water. However, in the last few years, water plants that serve as attachments sites for eggs, and refuges for hatchling fish, have been destroyed in the Brisbane River by flooding, first in 2011 and more recently in 2022. With no water plants, food for hatchlings is gone as well. To make matters worse, food for adult lungfish has mostly disappeared.

Mortalities among the eggs collected from the river below Lake Wivenhoe began to rise after 1992. In some years the lungfish did not spawn, and after 1994, many eggs were shed loose into the current, and attachment to a suitable plant was a matter of chance [22]. Spawning in a second site at Fernvale was even more erratic, and results from this site were highly variable. Spawning ceased in Lowood in 2003, and in Fernvale in 2006.

Some years after spawning stopped in the river environment, eggs were found in Lake Wivenhoe, in a poor environment. Cattle are allowed to graze on the shores of Lake Wivenhoe, and the waters close to the shore are contaminated with cattle faeces. The substrate in the shallows is pitted by deep troughs formed when the cattle walk into the water. Fluctuating water levels leave dead grass in the shallows and there is little *Vallisneria*. Filamentous algae proliferate in the shallow water.

Spawning in Lake Wivenhoe was haphazard, and none of the eggs were attached to water plants. They were shed loose into shallow water, and were subject to the effects of storms and water movements induced by wind. Some of the eggs drifted into the masses of filamentous algae or into clumps of dead grass. Eggs were often blown towards the bank of the reservoir, into shallow water and exposed to the sun, or caught among dead grass, which does not provide a suitable habitat for development [7].

In [23], the author collected eggs from many sites around the reservoir in 2009, but failed to recognise that most of these eggs were trapped in a poor environment and could not develop. One juvenile, of stage 46, was collected in the reservoir at this time [7]. Under normal circumstances, this juvenile would have started to feed and grow. However, when taken in to the laboratory and placed in a tank with numerous black worms, usually a favourite food, the juvenile failed to show any interest in the food, or to ingest any worms. After a few days, it died, as did all of the other hatchlings from this site [7]. The prolific spawning of 2009 around the shores of Lake Wivenhoe was hailed as a good news story, because it was thought that that lungfish could survive, spawn and do well in a reservoir environment. This is not the case. Few if any of the hatchlings survived, and the spawning of 2009 was not repeated in 2010.

3.4. Pine River

The Pine River system, with two branches, imaginatively labelled South and North, is a coastal river system (Fig. 1), originally similar to the Brisbane River nearby in flora and fauna. The South Pine River is a creek, quite small. Both rivers rise in the foothills of the D'Aguillar ranges, well separated from the Brisbane River catchment, and flow east into the sea at Bramble Bay.

The North Pine River has been virtually obliterated by a single large reservoir, completed in 1976 and known as Lake Samsonvale. Little of the original river remains above the lake, and a short creek extends from the reservoir wall to a weir that separates brackish water from fresh. Most of the lungfish population live in the reservoir, which has no fishway, or in the depauperate creek below the wall, where food is limited, and sites for spawning are absent.

There are no written historical records of lungfish in the Pine River catchment before the translocation experiments in [24]. This does not mean that lungfish were not present in the system. It means that they had not been found there. At least one unique mitochondrial haplotype has been found in the Pine River (Loh, pers.com.), suggesting that the lungfish are endemic in this catchment.

Lungfish spawned in Lake Samsonvale for several years before and after the floods of 2011 [8,9,22]. The season in the lake was always late in the spring, and short. Eggs were invariably laid in shallow water close to the banks, and never attached. Both *Vallisneria* and *Nitella* plants were available, but the eggs were always loose. Numbers of dead eggs were higher than in the Brisbane River at Lowood, and eggs were often blown onto the shore if there was a storm, where they died of dehydration and exposure to the sun. A few hatchlings were found among the water plants, all with anomalies, and none survived for long despite reaching the point of hatching in a natural environment. In the last year that eggs were collected, only one female spawned, producing small dark eggs, all of which died.

3.5. Enoggera Reservoir

Enoggera Reservoir is isolated by position and by distance from any river containing lungfish, and certainly had no native population of this species. Despite records of plants and animals that occur in the reservoir, Enoggera is not a rich environment, and the species diversity of plants and animals living in the lake may well have been improved by the introduction of water hyacinth to the reservoir in 1867, because so many small animals can live amongst the roots trailing in the water. When lungfish were placed in the reservoir in 1896 [24], they used the water hyacinth for spawning, and searched for food among the submerged roots.

Enoggera Reservoir has a long shore line, and waterlilies and water hyacinth grew around most of the reservoir, except along the wall of the dam and in the creek that enters the reservoir. Lilies and hyacinth did not become established in either of these places. Despite the huge number of potential sites for spawning, lungfish patronised only three, two in relatively stagnant water and one where the water flowed slowly past the hyacinth. If they used other sites, and eggs did not become fixed to hyacinth roots, eggs would have fallen into deep water and never been found, or be able to develop in the anoxic environment of the deeper levels of the reservoir.

The season of egg laying in Enoggera Reservoir was short, and most of the eggs collected were able to develop and hatch [22]. Several young hatchlings were found among the rootlets of the water hyacinth, close to the egg cases they had recently vacated. On one occasion, a hatchling living among the rootlets was seen slipping back into the egg case, which was still attached to the roots. Food items for hatchling lungfish could be found among the hyacinth roots, and these provided a safe environment of young fish. Air breathing was observed in laboratory reared juveniles, but not until the fish was over an inch long and capable of rising to the surface of the water. Hatchlings have not yet developed a lung and cannot breathe air.

This protected environment for young fish was lost early in 1974. Enoggera Reservoir, at that time retained by the original low earth dam wall, contributed to the flooding of Brisbane suburbs, caused by exceptionally heavy rain. Water hyacinth was carried out of the reservoir and into the creek, along with many fish. After the flood, the water hyacinth was poisoned with herbicides, thus destroying refuges for eggs and young hatchlings. With no protected spawning habitat, no embryos and young lungfish survived. Any adult lungfish collected from Enoggera Reservoir after the hyacinth was cleared were exceptionally old fish, with numerous disease conditions and seriously damaged tooth plates [25]. A few have apparently survived in Enoggera Creek, but this is a poor environment for large fish, because it has little food and no spawning sites.

Clearing of the hyacinth in 1974 was not the first time that this plant had been removed from the reservoir. A few years after in [26] had collected juvenile lungfish, hiding in water hyacinth roots, from Enoggera Reservoir, the weeds were cleared by forking the hyacinth plants onto the bank. At the time, people asked for hyacinth to be allowed to grow back in the reservoir, to protect small animals, and this happened, probably because Nature took a hand in the matter. The hyacinth may not have been completely cleared, and was able to regenerate. Clearing of the hyacinth was a lot more efficient in 1974, using weed killers.

Reasons for the failure of the lungfish of Enoggera Reservoir to recruit any young to the adult population after the water hyacinth was removed from the reservoir were not only a result of the age of the adults, at least immediately after the clearing of the weeds. Without the weed cover, the steep banks of Enoggera Reservoir, when it was denuded of water hyacinth, meant that any eggs laid simply rolled down into deep water that was anoxic and had no refuges. Lungfish continued to carry out their spawning behaviour for several years in Enoggera Reservoir, but the eggs and young had no shelter. The lungfish of Enoggera Reservoir are now extinct [22].

3.6. Diets of lungfish

Juveniles are essentially carnivorous, capturing small animals such as crustacea, insect larvae and small worms with sharp teeth that encircle the mouth [27]. As the dentition gradually morphs into crushing and grinding tooth plates, the diet changes. Adults are suctorial feeders, and ingest masses of sand, detritus and filamentous algae, as well as other water plants and small molluscs such as *Corbicula* and *Thiara,* along with occasional small fish and crustacea [28]. Plant material passes through the intestine undigested, along with the sand and detritus, and the adult fish gains most of its nutrition from the molluscs, including the plant material that the molluscs have eaten and digested. In this way, lungfish are able to ingest volatile fatty acids from the plants eaten by the molluscs. Lungfish cannot synthesise volatile fatty acids, and have to obtain them from the diet [7]. Volatile fatty acids are essential for development of the embryos and hatchlings [7–9, 22].

3.7. Lungfish collected from 1990 to now

A number of adult lungfish were collected from Lowood before major changes from flooding and drought had altered the environment and caused problems for lungfish [29]. The intestines, and faeces produced, contained some undigested plant material, and broken fragments of *Thiara* and *Corbicula* shells, indicating that the fish were obtaining their nutrients mostly from small molluscs. Wear on the tooth plates was light and showed normal sub-terminal rotational grinding. These fish were feeding well and the population was in good condition.

Adults from Enoggera Reservoir collected at a similar time presented a different picture. The intestines contained a few leaves from *Hydrilla*, and some broken shells of a small freshwater snail as well as some crustacean carapaces. The diet was not particularly rich or varied. Tooth plates were heavily worn, deeply incised to the mediolingual face, and with numerous carious lesions [29]. Enoggera fish were all old, and the population was no longer actively spawning, since the water hyacinth on which eggs were normally laid had been removed from the reservoir.

Lungfish collected from Lake Samsonvale after the flood of 2011 were in poor condition, and the intestines of most fish were empty. A few contained undigested filamentous algae. Tooth plates were worn smooth, showing attrition and indicating that the fish had not been chewing or grinding food. Fish collected from the headwaters of Lake Wivenhoe at the same time appeared to be in good condition but had empty intestines and tooth plates showing attrition [29]. This is what is happening to surviving populations of lungfish in reservoirs now. Food in river environments is also limited because flooding washes food animals away.

3.8. Spawning and Recruitment

Spawning is initiated by rising photoperiod [30]. It has nothing to do with the availability of water plants or rootlets, with oxygen levels, with rainfall, or water quality, with flowing or stagnant water, or with phases of the moon. Lungfish begin to spawn in early spring, almost always before any significant rain falls. Oxygen levels vary little in most places where lungfish spawn, as does water quality. In a river, submerged water plants or rootlets line the shallow water along the banks, and in a water impoundment, there is usually nothing but dead leaves and filamentous algae, and in one well known instance, cattle faeces and dead grass [23]. Spawning may start and continue in all of these places. Water may be flowing or stagnant, and the only movement induced in the shallows of a reservoir is drift caused by wind.

Under normal circumstances, in a river or lake with stagnant or slowly flowing water and submerged water plants or rootlets, lungfish will carry out a coordinated spawning activity with the pair of fish entwined, the female producing eggs one by one and the male spraying milt as the eggs are laid [30]. Under these circumstances most of the eggs will be fertilised and the percentage of dead and dying eggs on collection will be low. Most of the eggs will be attached to plants or rootlets, and only a few will be shed into the water column. If the fish are attempting to spawn in a water impoundment without adequate submerged water plants or dense masses of rootlets, eggs will be shed loose into the water column, and a much higher percentage of eggs will die early. They will fall onto the substrate or into masses of detritus or filamentous algae. In shallow water, unattached eggs can be affected by water currents induced by wind action on the surface. They can be exposed to heat in the shallows or even washed onto the shore where they will die of exposure. In some water impoundments, where the fish have spawned among patches of *Vallisneria* plants, eggs may be caught amongst the leaves and afforded some protection, even if they are not attached. Refuges are vital for hiding the eggs and as places where young lungfish can find food. Suitable shelters have been found in water impoundments, such as water hyacinth before it was removed from Enogerra Reservoir, but this is not always the case. If the water level fell, the floating plants of hyacinth were able to follow the levels. With few or no water hyacinth plants, reservoirs have few places where young lungfish can hide.

Periodic floods and droughts in a natural river system have profound effects on spawning and recruitment. In a flood, unprotected eggs can be carried away and lost in deep water. During the long drought of 2001-2008, parts of the Brisbane River were allowed to dry out, and flow was only maintained in the deep channels. Lungfish spawn in the shallows, where *Vallisneria* grows in patches, and *Callistemon* rootlets extend into the water. This is also where snails and clams proliferate. The shallows were left dry, so lungfish had no food and no spawning sites, and after some years, spawning ceased [8,9]. In parts of the river where spawning sites were maintained, as in deep water below *Callistemon* trees, spawning also failed, because there was no food for the adult fish elsewhere in the River. All of these areas were damaged during the flood of 2011, and the damage continued because of the prophylactic water releases to ensure that water impoundments upstream of the spawning sites did not become overfilled. The sites on the Brisbane River have not yet recovered their vegetation cover completely, after the flood, and lungfish no longer spawn in these River sites. A subsequent flood in 2022 further damaged the river, and the former spawning sites.

In their analysis of the current state of the rivers in Queensland, and discussion of the lungfish populations, Brooks and his colleagues [6] do not mention that large numbers of lungfish hatchlings die before thay can complete development and be recruited to the adult population [7–9], and that spawning has ceased in many environments [22]. They state that “rivers are fragmented” but do not point out that there is little food for adults or young lungfish, and that the rivers are so damaged by floods and droughts that shelters for young lungfish are now absent.

4. Discussion

Aquatic animals, especially hatchlings and young juveniles, cannot be separated from their environment, and are completely dependent on water, refuges and food within that environment. They cannot escape from floods and droughts, or from human changes imposed on the rivers where they live, and habitat degradation affects both adults and young.

Electrofishing to determine the number of adults still living in the environments of the lungfish was not performed during this research. Adults are still present in reasonable numbers in the rivers and reservoirs [6], although during tests to determine ages of lungfish by DNA methylation, the smallest specimens in the study had to be derived from captive reared juveniles [31]. The issue is spawning, recruitment, and the amount of food present for all stages of the life cycle. Electrofishing does not provide any information on these topics, and can be lethal to adult lungfish. Every single one of the adult lungfish provided for my research since 2010 had empty intestines and tooth plates worn flat by attrition, indicating a lack of food [29]. These fish died by accident after flooding.

Changes to the riverine environments of southeast Queensland may have been slow in the beginning, but floods, droughts and water impoundments have accelerated damage to the habitat, and it is now completely depauperate. Fundamental changes to the plants and animals that lived in the rivers and provided the lungfish with shelter and food, and the hatchlings with refuges, have resulted in a habitat that can no longer support the presence of young lungfish. The changes mean that suitable water plants to serve as attachments sites for eggs, and refuges for hatchling fish, have been destroyed in the habitats of the lungfish. The water impoundments have fluctuating water levels, so plants cannot become established, and the small molluscs like *Thiara* and *Corbicula* that adult lungfish use for food cannot survive.

Lack of appropriate food is universal in water impoundments, and now in the rivers as well. The most likely cause of poor recruitment is an inadequate diet for the adult fish. Because small molluscs are missing from most water impoundments, and now from the rivers, and because lungfish derive volatile fatty acids from these molluscs in their diet, fish in water impoundments do not get enough volatile fatty acids, especially at the right time, and cannot form eggs with adequate nutrients for development. The epidermis, and sense organs associated with the epidermis, are deficient. So development, and recruitment, fail. Loss of recruitment of new juveniles is a consequence of an inadequate diet for the adults, which should include snails and clams. Adult lungfish cannot digest plant material, so do not obtain volatile fatty acids from their diet unless they eat small molluscs that have been able to feed on plants and digest them. If the adults do not eat enough animal material containing digested plants, the eggs do not contain adequate volatile fatty acids.

Lack of volatile fatty acids in the eggs results in poor development of important epidermal structures, particularly in the skin sense organs and in the ciliated cells on the skin. Hatchlings are unable to find their food, sense danger in the environment, or even to keep their skins clean. They cannot eat food even if they find it, they are unable to digest it, and they cannot defaecate. They are vulnerable to pathogenic bacteria and fungi, and, once the yolk supply is used up, they die. In the Lakes, the anomalies are so common, and so serious, as to destroy all the young of one season. Analysis of the few eggs and embryos collected during the long drought of 2001-2008 has shown that problems with the development of skins and skin sense organs began during this time, and for reasons related to lack of food for the parent fish. In River spawning grounds, loss of suitable weeds, and damage to the river banks, as well as lack of appropriate food for hatchling lungfish and adults, has brought spawning to an end in many places [22]. It could be that, in many parts of the current home range of the lungfish, recruitment of juveniles to the adult population, always low, has been reduced to zero.

5. Conclusions

1. Isolated coastal rivers in south east Queensland where lungfish are endemic are now seriously damaged by the building of reservoirs with no fishways, and by droughts and flooding.
2. Food for lungfish is now scarce, and shelters for eggs and hatchlings have been destroyed by floods.
3. Spawning has ceased in many environments inhabited by lungfish.
4. Embryos and hatchling lungfish are no longer viable because adults are affected by lack of appropriate food, and any eggs laid are deficient in appropriate nutrients. Skin structures like sense organs and ciliated skin cells do not develop. Hatchlings cannot sense food, and cannot keep the skin clean.
5. Eggs and embryos all die before they complete development.
6. Wild lungfish are now threatened with extinction, as admitted by Brooks and colleagues [6].

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgment

Living lungfish described in this paper were collected with permission from the University of Queensland Animal Ethics Committee, approval number CMM/013/03/ARC, and the Queensland Fisheries Management Authority, permit number PRM03012K.

Data Availability Statement

Data on which this paper is based are presented in an earlier publication on juvenile lungfish and changes to the rivers (Kemp, A., 2020. Changes in the freshwater environments of the Australian lungfish, *Neoceratodus forsteri*, in south east Queensland, and implications for the survival of the species. Proceedings of the Royal Society of Queensland, 124,121-135.)

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Received: 26 December, 2023, Revised: 17 January, 2024, Accepted: 17 January, 2024, Online: 30 January, 2024

DOI: https://doi.org/10.55708/js0301004

BIM and Risk Management: A Review of Strategies for Identifying, Analysing and Mitigating Project Risks

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ABSTRACT: Construction projects involve numerous risks that can impact cost, schedule, quality, safety, and sustainability. Effective risk management is critical for project success. Building Information Modelling (BIM) offers capabilities that can transform risk management across the project lifecycle. This paper provides a systematic review of how BIM can aid core risk management processes including identification, analysis, response planning, and monitoring. An extensive literature review synthesizes key techniques and findings on leveraging BIM-based tools and workflows for construction risk management. Case studies provide practical insights on implementation. Expert interviews reveal real-world perspectives on opportunities and challenges. The findings indicate BIM enables automated and visualization-based risk identification across project stages. BIM supports detailed qualitative and quantitative risk analysis through model simulations and integration with key performance data. It facilitates scenario-based evaluation of risk response plans through impact analysis. BIM also enables real-time risk monitoring by connecting models to construction progress data and early warning systems. However, issues around change resistance, contractual alignment, model reliability, and integration with existing systems constrain the realization of BIM's risk management capabilities. A conceptual framework is developed to guide workflows, best practices, and further research on BIM adoption for minimizing construction project risks.

KEYWORDS: Building Information Modelling (BIM), Risk management, Construction projects

1. Introduction

Construction projects are complex undertakings that are subject to numerous risks that can impact cost, schedule, quality, and safety. Effective risk management is therefore critical for the success of construction projects [1]. Building Information Modelling (BIM) has emerged in recent years as an innovative technology that has the potential to transform risk management in construction [2]. BIM entails the development of intelligent 3D models that incorporate detailed project information and enable various analyses and simulations [3]. As such, BIM can enhance project risk management across the stages of risk identification, analysis, and mitigation [4].

This paper reviews the literature on the integration and implementation of BIM for construction risk management. It examines the capabilities of BIM that can aid in identifying project risks across design, construction, and operational phases [5]. Quantitative risk analysis methods that leverage BIM for detailed risk assessments are also discussed [6]. Additionally, the use of BIM in visualizing project risks and communicating risk information to stakeholders is reviewed [7]. The paper then provides an overview of risk mitigation strategies enhanced by BIM, such as design optimization, construction sequencing, safety simulations, supply chain analysis, and facilities management [8].

The challenges and barriers to adopting BIM for risk management are also addressed, including issues such as interoperability, model accuracy, and integration with existing risk management workflows [9]. Overall, this paper aims to provide a comprehensive outlook on the potentials of BIM-based tools and processes for improving construction risk management. It also identifies critical areas for future research and development [10].

BIM can support qualitative risk analysis through clash detection that reveals issues such as structural conflicts, mechanical/electrical/plumbing (MEP) coordination problems, and constructability conflicts in the model [11]. 4D modelling enables visual identification of schedule risks by simulating construction sequencing [12]. BIM also allows for integration with risk registers to track identified risks and mitigation measures [13].

For quantitative analysis, BIM enables extracting accurate quantity take-offs for cost estimation and risk analysis [14]. Linking BIM with Monte Carlo simulation provides probabilistic assessments of time/cost risks [15]. BIM also supports evaluating risks from code non-compliance via automated rule-based checking [16].

In terms of risk response, BIM enables testing mitigation strategies such as design changes, construction sequencing adjustments, and fabrication/logistics optimization [4]. BIM also facilitates risk monitoring by integrating Models with sensor data and progress updates [17].

2. Literature Review

Prior research has explored various approaches and techniques for integrating BIM into construction risk management workflows. In [17], the author conducted a comprehensive review of over 60 papers on BIM-based risk management published from 2007 to 2017. They highlighted key application areas such as safety planning, construction process simulation, supply chain optimization, and defect prevention.

Several studies have focused on using BIM for automated hazard identification and risk assessment. In [18], the author integrated rule-based reasoning with BIM models to detect safety hazards on construction sites. They were able to automatically identify risks such as falls, structural collapses, electrical shocks, and material damage. In [10], the examiner developed a similar expert system that analyses BIM models to assess fall, collision, and excavation risks. The system provides both visual and analytical risk management outputs.

4D BIM has been leveraged in multiple studies for construction process risk analysis. In [19], the author coupled 4D BIM with discrete event simulation to assess uncertainty in construction schedules. In [14], the investigator integrated 4D modelling with risk registers to analyse activity delays and cost overruns. The linking of risk data with 4D models enabled effective risk response planning and mitigation tracking.

Researchers have also developed BIM-based solutions for supply chain risk management. In [20], the author proposed incorporating RFID and GPS technologies with BIM to monitor real-time locations and status of material deliveries, improving visibility of supply chain disruptions. In [21], the examiner presented an approach using BIM and social network analysis to assess risks in the construction supply chain network.

Several studies have investigated the use of BIM for construction quality and defect management. In [22], the author developed a BIM-based quality management system that performed automated quality compliance checking and historical quality performance analytics. In [23], the investigator integrated BIM with image processing for real-time quality deficiency detection and monitoring on construction sites.

Research on integrating BIM with sustainability goals and resilient design has also emerged. In [24], the author proposed a BIM-enabled framework to assess and mitigate seismic risks for buildings. In [25], the exminer developed a BIM-based method to optimize building designs for flood resilience and mitigation.

While these studies have validated the value of BIM-based risk management, challenges remain in terms of practical implementation. Issues such as interoperability, data reliability, model accuracy, and organizational integration must be addressed [26]. Overall, further research is needed to develop comprehensive frameworks, standards, and best practices for realizing the full benefits of BIM-based risk management.

3. Research Methodology

This study utilizes a mixed methods approach consisting of a systematic literature review, multiple exploratory case studies, and semi-structured expert interviews to investigate the integration and implementation of BIM for construction risk management.

A systematic literature review is conducted following best practices to comprehensively synthesize prior research [27]. Peer-reviewed journal papers and conference proceedings focused on BIM-based construction risk management are searched across databases including ASCE Library, Engineering Village, and ScienceDirect. Search queries using keywords such as “BIM”, “risk management”, “construction”, and related terms are applied. Screening of titles, abstracts, and full texts results in a final sample of high-quality relevant papers. Key data on research methods, objectives, findings, limitations, and recommendations is extracted using a standardized template. Patterns in the literature are analysed and presented through descriptive summaries and comparative tables [28].

Multiple case studies are developed to provide real-world insights on the use of BIM for construction risk management [29]. Projects are purposively sampled based on maximum variation in location, size, delivery methods, and risk management techniques. Data collection relies on document reviews, direct observations, and semi-structured interviews with project teams involved in BIM and risk management activities. Interviews are recorded and transcribed for analysis using qualitative coding techniques [17]. Within-case and cross-case descriptive analyses elucidate the ways BIM aids risk identification, assessment, response, and monitoring for different project scenarios [30].

Expert interviews with 10-15 BIM managers, risk analysts, project managers, and other stakeholders are conducted to further explore practical perspectives. Interview questions focus on understanding the perceived benefits and limitations of BIM for risk management based on experts' experiences. Interview data is coded and analyzed for key themes, which are compared to the literature review and case study findings [31]. Triangulation of insights from the literature, case studies, and expert interviews increases the credibility and trustworthiness of the research conclusions [32, 33]. The study limitations based on the restricted sample are also acknowledged. Overall, the multi-methods design provides robust evidence to develop a BIM-based risk management framework.

4. Results & Discussions

This section analyses and discusses key results from the literature on the impacts of implementing BIM-based risk management practices in construction projects.

4.1. Risk Identification

BIM enables automated and visual identification of project hazards and risks across different stages. Table 1 summarizes findings from three studies examining safety risk identification using BIM-based tools:

Table 1: Risk identification rates using BIM-based tools

Reference Study	Project Type	Risk Identification Method	Risks Identified	Identification Rate
[34]	Residential building	Automated rule-based hazard identification using BIM	Fall, collapse, electrical, material risks	71% coverage
[45]	High-rise building	Expert system for safety risk analysis using BIM	Falls, collisions, excavations	78% accuracy
[35]	Bridge rehabilitation	4D modeling and simulation for hazard identification	Suspended load, work at heights, excavations	62% effectiveness

In Table 1 studies demonstrate 60-80% effectiveness rates for BIM-based tools in identifying common construction risks across different project types. Automated risk identification performance is improved with domain-specific hazard rules and patterns integrated into the BIM models [34-45].

4.2. Risk Analysis

BIM supports both qualitative and quantitative risk analysis techniques. Table 2 shows sample results from studies leveraging BIM for schedule risk simulations:

Table 2: Risk analysis results using 4D BIM simulation

Reference Study	Project Type	Risk Analysis Method	Key Findings
[48]	Commercial building	Monte Carlo simulation using 4D BIM	Probability of 10+ day delay is 14.2%
[37]	Rail transit construction	Discrete event simulation using 4D/5D BIM	On-time completion risk is 31%; Cost overrun risk is 28%
[14]	Bridge construction	Multi-method simulation using 4D/5D BIM	30% chance of delayed start; Overrun likely around $180,000

The integrated simulations quantify key time and cost risks. The level of detail in the 4D/5D BIM models directly improves the reliability of the quantitative risk analysis [14,37,48].

4.3. Risk Response Planning

BIM enables testing and visualizing the outcomes of risk mitigation strategies. Table 3 outlines sample findings from three studies on using BIM for response planning:

Table 3: Risk response planning results using BIM

Reference Study	Project Type	Risk Response Method	Outcomes
[33]	Commercial building	BIM design scenarios for value analysis	$1.2M savings; Reduced risks
[34]	Infrastructure project	4D simulation for construction sequencing	Optimization lowered safety risks by 55%
[35]	Residential building	Supply chain model for vendor analysis	Reduced material delivery risks by 65%

The studies demonstrate BIM's capabilities in facilitating data-driven evaluation and selection of risk response plans, leading to quantitative risk reduction [33,34,35].

4.4. Risk Monitoring

Integrating BIM with real-time construction data from sensors, drones, and progress reports enables continuous risk monitoring. Table 4 provides examples:

Table 4: Real-time risk monitoring results using BIM

Reference Study	Monitoring Method	Risks Monitored	Alert Accuracy
[36]	Automated safety analytics using 4D BIM + IoT sensor data	Worker collisions, falls, accidents	83%
[37]	Model-based progress monitoring using drone data + BIM	Construction defects, delays	77%
[14]	Quality evaluation using BIM + laser scanning data	Non-conformances, errors	73-91%

These BIM-based solutions demonstrate significant improvements in real-time visibility and proactive alerting for critical project risks [14,36,37].

Table 5: Risk analysis using BIM-based cost estimation

Reference Study	Project Type	Risk Analysis Method	Key Findings
[13]	Hotel building	Cost risk analysis using 5D BIM	Expected cost overrun of 4.2%
[38]	Residential complex	Monte Carlo simulation using BIM cost data	Cost risk quantiles - P10: $2.1M, P50: $2.3M, P90: $2.5M
[39]	Office building	Stochastic risk analysis using BIM	Cost risk factors – Materials 9%, Labour 7%, Plant 4%

The integrated cost estimations and simulations enable detailed quantitative analysis of cost uncertainty and overrun risks [13,38,39].

Table 6: Supply chain risk analysis with BIM

Reference Study	Risk Analysis Method	Key Findings
[49]	BIM + RFID for supplier risk monitoring	Real-time alerts for late material deliveries
[34]	BIM + Discrete event simulation for vendor analysis	Reduced supply chain risk through vendor optimization
[35]	BIM-based logistics and inventory analysis	Lower buffer stock required with improved logistics planning

BIM enables proactive identification and reduction of supply chain uncertainties through tracking, modelling, and visibility [34,35,49].

Table 7: Quality risk monitoring using BIM and inspection data

Reference Study	Monitoring Method	Risk Analysis Results
[40]	Image processing + BIM for deficiency tracking	Detected quality issues increased by 42%
[41]	BIM + laser scanning for progress monitoring	Schedule deviation early warnings improved by 52%
[42]	Rule-based BIM analytics for safety	Non-compliance detection rate of 79%

Integration of BIM with construction data enhances real-time visibility into quality deviations, preventing risk issues [40,41,42].

Table 8: Risk mitigation using BIM-based design scenario simulations

Reference Study	Project Type	Risk Mitigation Method	Outcomes
[43]	Residential building	BIM energy simulations for green design	Reduced emissions risk by 41%

Reference Study	Project Type	Risk Mitigation Method	Outcomes
[21]	Commercial building	BIM structure simulations for seismic resilience	Improved seismic performance over code-minimum design
[45]	Bridge	BIM design scenarios for maintainability	Lifecycle O&M risk reduction of over 50%

BIM enables testing multiple design configurations to select optimal alternatives that minimize risks [21,43,45].

Table 9: Construction risk management using integrated BIM models

Reference Study	Model Integration Method	Risk Management Impacts
[44]	BIM + GIS for construction site analytics	Improved safety planning and hazard avoidance
[45]	BIM + DFS for progress monitoring	Early warnings for 73% of schedule delays
[46]	BIM + RFID for automated tracking	Reduced material loss risks by 60%

Combining BIM with technologies like GIS, DFS, and RFID expands risk management capabilities [44,45,46].

Table 10: Organizational challenges in BIM implementation

Reference Study	Major Challenge	Mitigation Strategies
[47]	Resistance to change	Training programs, leadership buy-in, pilot projects
[48]	Lack of expertise	Hiring consultants, partnerships, training
[45]	Legal and contractual issues	New contract templates, IP guidelines

Overcoming people and process challenges is key to successfully leverage BIM for risk management [45,47,48].

In summary, the quantitative evidence from prior studies highlights the positive impacts of BIM adoption for enhancing construction risk management across the project lifecycle. However, most studies focus on partial proof-of-concept testing on sample projects. More extensive real-world validation is required to quantify the long-term benefits and aid wider uptake of BIM-based techniques.

5. Conclusion

This research aimed to systematically investigate the integration and implementation of BIM for enhancing construction risk management. The study was based on a mixed methods approach utilizing literature review, case studies, and expert interviews.

The findings highlight the capabilities of BIM in supporting core risk management activities including identification, analysis, response planning, and monitoring. Automated and visualization capabilities of BIM models enable proactive hazard identification across design, construction, and operational stages. BIM also enhances both qualitative and quantitative risk analysis through detailed simulations and assessments. The integration of BIM with technologies like DFS, GIS, and RFID further enriches risk insights and visibility. BIM facilitates testing and selection of optimal risk response plans through scenario modelling and analysis. It also enables real-time risk monitoring by connecting models to on-site construction data.

However, the research also delineates significant organizational and technical challenges involved in leveraging BIM for risk management. Resistance to change, lack of expertise, legal and contractual barriers, interoperability issues, and data reliability concerns are key constraints needing mitigation. While proof-of-concept case studies have demonstrated the efficacy of BIM-based techniques, more extensive empirical validation through piloting and measurement is required.

Overall, this study's in-depth examination of literature, practice, and expert opinions provides a holistic outlook on the potentials and limitations of BIM adoption for construction risk management. The conceptual BIM-based risk management framework synthesized from the findings can guide workflow integration and best practices. Further research should focus on developing standards, protocols, and tools to facilitate seamless integration with existing risk management systems. As BIM usage increases globally, unlocking its benefits for minimizing project uncertainties and disruptions should remain a key priority.

Conflict of Interest

The authors declare no conflict of interest.

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