A Planning Decision Support Tool for Evaluation and 3d Visualisation of Building Risks in Flood Prone Areas

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Keywords: Flood Risk, Visualisation, BIM, GIS, Building

SUMMARY

Floods are the most common and costliest natural disasters around the globe. The severity of the recent events (e.g. 2010/2013 Queensland floods) and the predicted increase in the frequency and intensity of future floods have highlighted the need for their effective management levels and establishing flood resilience in the society. Buildings, on the other hand, have special importance in this context and their damage forms a significant portion of the overall cost of flood damages to the community. Additionally, the strength and performance of buildings are essential to the safety of people. Accordingly there has been a recent call for higher safety standards in building construction for mitigating their potential flood damages and protecting people in such disastrous situations.

The Building Code of Australia (BCA) has recently developed a number of requirements for ensuring the flood resilience of new buildings. However, the focus of the current Australian and New Zealand standards is mainly on the design for wind and earthquake events with little attention to designs mitigating against flood impacts. On the other hand, engineers/designers and the responsible authorities (e.g. councils and referral authorities) have limited decision support tools that can effectively evaluate the flood risks of a building at its planning stages. The majority of the existing tools are suitable for assessment of potential damages and risks where a large number of buildings are in focus. Although some tools can be applied on an individual building basis, they either use generalisation that ignores the unique characteristics of the building construction or are limited to only certain types of flood damages. As a result, simple and approximated models are commonly employed for this purpose with limited use for building planning and for assessing its suitability in flood prone areas.

This paper presents and discusses the development of a planning decision support tool for assessing the flood risks to a building. This prototype system has a multi-tier architecture and is designed according to the analysis of general requirements for assessment of risks to a building. By integrating Building Information Model (BIM) with Geographic Information Systems (GIS) and employing civil engineering principles, this tool supports a detailed assessment and 3D visualisation of the cost, mode, and the location of damages to a proposed building and determining the risks to its components. The proposed tool was evaluated using expert opinion and a case study. This evaluation showed that the system can facilitate decision-making for a range of technical and non-technical decision makers and support a number of applications in the planning and development process to improve the resilience of new developments.

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1. INTRODUCTION

Floods are the costliest and most frequent natural disasters in Australia and around the world (Jha et al., 2012). The lessons learnt from recent floods in Queensland have underlined the limitations of management of such hazards via sole focus on containment strategies using flood walls, levees, or other structural measures (Merz et al., 2010; Birkmann et al., 2013). Accordingly, modern flood management techniques adopt Flood Risk Management (FRM) as their central framework. Through focusing on both components of flood risk (i.e. hazard and the vulnerability of elements at risk), FRM intends to identify and, via adopting suitable measures, mitigate the risks for various built environments.

In the management of flood risks, particularly in the urban context, a special emphasis is made on buildings. This is due to the significance of buildings to the economy as well as their large share in the overall flood damage bill of the affected economy (Dewals et al., 2008; Messner et al., 2007). In addition, empirical evidence suggests a strong link between the number of fatalities from floods and the failure of buildings. Therefore, the structural stability of buildings have been recognised as a crucial factor for maintaining the safety and well-being of people (Grundy et al., 2005; Dewals et al., 2008). According to these drivers, local governments and the Building Code of Australia (BCA) require building designs to conform to a set of minimum performance requirements for ensuring their flood resilience (Van de Lindt and Taggart, 2009; ABCB, 2012). Despite these requirements, the Australian and New Zealand construction standards provide few guidelines for design against flood impacts and only focus on wind, fire and earthquake. Consequently, detailed response analysis for individual buildings is required to detect non-conforming developments and in order to shed light on the potential areas of improvement (CSIRO, 2000; Becker et al., 2011). This is typically performed as part of Flood Damage Assessment (FDA) or vulnerability assessment processes that by provision of a better understanding of weak points in designs, they enable decision-makers to adopt building and/or property level measures to increase their flood resistance. Such measures can lower the costly retrofitting and redesign at the later stages in the building lifecycle. Additionally, they can facilitate a quicker post-disaster restoration and reinstatement of buildings resulting in a cheaper and less stressful resettlement of their residents (Matthew, 2005; Lamond and Proverbs, 2009).

Amirebrahimi et al. (2015b) have highlighted the ineffectiveness of the existing tools and their limitations for use in detailed assessment and communication of potential flood damages and risks at a building level. These limitations exist mainly due to a number of underlying factors such as (a) generalisation of buildings and ignoring the unique design of buildings in the analysis according to the use of unsuitable data inputs, (b) incomplete analysis of risks by not accounting for both structural members' failure and the water contact damages, and (c) ineffective communication of mode and location of potential flood impacts on a building that can improve the understanding of the nature of risks and their possible treatment solutions. Accordingly, in practical applications, the relevant authorities tend to employ simple - but scientifically questionable - frameworks to assess the suitability of developments in flood prone areas. As an example, many councils across Australia as well the Melbourne Water (the referral authority in the Metropolitan Melbourne area) use maximum allowable above-floor-water-depth (known as "freeboard") for accepting development proposals for construction (Melbourne Water, 2014). Although this conservative approach seems to be a practical solution, the decisions are generally made with little evidence and attention to the actual resilience of the building, its design and construction materials.

For addressing the discussed limitations of the existing models/tools, an integrated flood damage/risk assessment framework has been proposed in an earlier work of the authors (refer to Amirebrahimi et al., 2015b). This framework was designed according to the well-established theories in a number of related domains (e.g. civil engineering, hydrology, and geospatial analysis tools). It provides necessary guidelines for detailed assessment and a 3D visualisation of flood risks to a building and based on its unique characteristics and behaviour against floods.

According to the foundation laid by the framework, a decision support prototype system was developed for a detailed assessment and 3D visualisation of risks to a given proposed building in a flood prone area. The main intended objective of the designed tool was to provide a range of decision-makers (e.g. engineers, councils and referral authorities) with evidence about the risks to a building to support crucial decisions during its planning, design and approval stages. This paper provides the details of the development of this system and demonstrates its application in a real world decision making planning scenario.

In the remainder of this paper, first the methodology for the development of the tool is presented. Next, according to the guidelines of the selected methodology, the conceptual design of the tool and its architecture are discussed in detail. This is followed by the explanation of the development of the prototype system and its functional overview. The paper then discusses the results of the evaluation process for the proposed tool using expert opinion and a real case study. Finally, the conclusions are presented and the future research directions are proposed.

2. METHODOLOGY

The development of the flood risk decision support system was undertaken according to the principles of "prototyping" (Nunamaker et al., 1990-91). This methodology is popular in the software engineering domain for designing and development of information systems and consists of five phases. As Figure 1 illustrates, first a conceptual framework for the prototype is designed. It describes the functionalities and requirements of the system and the potential solutions from relevant disciplines for its development. Next, the system architecture is decided upon and the functionalities of the system and their interrelationships are designed. In the third step, the system is analysed and refined by assessing alternative solutions. According to this design, the prototype system is developed in the fourth step. Finally, the system is evaluated using appropriate methods to test its effectiveness for practical applications. This process of development of flood risk analysis tool groups these steps into three generic steps namely the *Conceptual design*, *Development*, and *Evaluation* phases (see Figure 1). Sections 3 to 5 in this paper explain these phases for developing and testing the flood risk analysis tool.

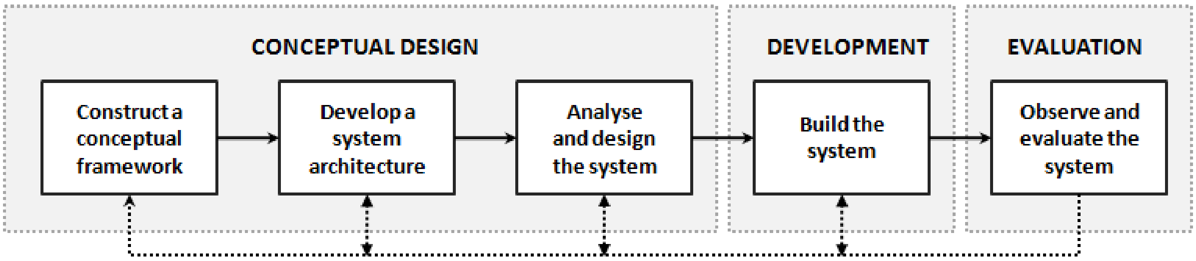


Figure 1: Prototyping methodology (modified from Nunamaker et al., 1990-91)

3. CONCEPTUAL DESIGN

The conceptual design of the tool, as illustrated in Figure 1, includes steps as mentioned above. This section explains each step in detail as related to this project.

3.1. Construction of conceptual framework

To design the conceptual framework, first the practical use cases pertinent to different potential users of the tool as well as the required processes for risk estimation (i.e. damage assessment and risk calculation) were investigated. For understanding these processes, an initial study was undertaken to detail the Australian building typology within the flood prone areas in the country. Next, for particular building types, the susceptibility of their components to flood loads and water contact were investigated and accordingly, engineering methods for the assessment of flood damages to each were identified. Additional effort was made to compute the extent of water infiltration as this was identified as a prerequisite for many of these damage assessment processes. Through selection of the best solutions amongst the potential alternatives and the logical integration of these processes and calculations for damage and risk estimation, the conceptual design of the framework was completed. This framework explains the process of assessment of flood damages and risks to a building in four phases: data preparation, flood physical damage assessment, quantification of damage and risk, and communication and reporting. Furthermore, the framework requires a comprehensive data foundation to support the data inputs of its processes. Accordingly, a new data model was designed that can bring together detailed three-dimensional building information and flood parameters from Building Information Models (BIM) and Geographic Information Systems (GIS). For the details of the framework and the data model reader is referred to Amirebrahimi et al. (2015a, 2015b).

3.2. Design and analysis of system architecture

According to the formulated use cases in the initial stages of research, a number of functionalities were envisioned for the flood risk assessment system. They include:

- The system should allow for importing data requirements of the system;
- It should support dynamic (temporal) analysis of structural and non-structural building elements against flood loads and the water contact effects;
- It should allow damage cost and risk estimation for individual building assemblies as well as the entire building; and
- It should allow detailing the location and mode of damage to individual building assemblies (at different stages of the flood and in overall).

They, along with the identified processes, form the basis of the design of the architecture of the prototype system. By investigating a number of alternative designs, due to its flexibility and modular structure, the use of layered architecture was decided for the development of the flood risk assessment prototype system. As Figure 2 illustrates, this architecture is made of four layers; i.e. *Data Layer (DL)*, *Data Access Layer (DAL)*, *Business Layer (BL)*, and the *Presentation Layer (PL)*.

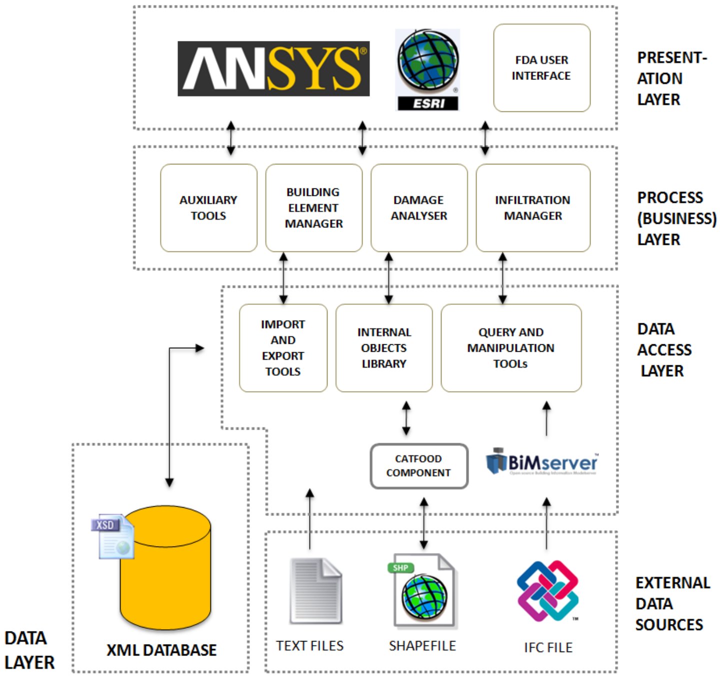


Figure 2: Flood risk assessment prototype system architecture

The Data Layer of the prototype contains the required spatial and non-spatial data to undertake the damage/risk assessment and visualisation processes. The core aspect of this layer is an XML database which was designed and implemented in accordance to the developed data model (see Section 3.1). Additionally, other text, ShapeFiles or IFC files (BIM standard exchange format) are considered as supplementary data sources and included within the scope of this layer.

Data Access Layer (DAL) is the intermediate layer between the Data and Business layers and provides simplified access and retrieval methods for data that is stored in the data storage (e.g. database or files). DAL also manages the internal library of objects that in addition to other required data structures for system's internal use, correspond to the concepts designed in the XML database. These objects unify the view of data at lower levels of the architecture (which may be in different formats) for use at the higher layers. Furthermore, DAL contains a number of modules to perform data transformation, data manipulation and querying. In addition to in-house code, a number of open source components like BIMServer (2015) and CatFood project (Available from shapefile.codeplex.com) were used for implementing these modules. BIMServer, as a platform, is developed for sharing, visualising and working with BIM models. On the other hand, CatFood is an open-source library to manipulate ShapeFiles for developing GIS applications.

The Business Layer is responsible for maintaining the logical processes and rules related to the required calculations. With direct interaction with the DAL mediators, the BL modules fetch their required data from the DL and perform various functions of the prototype including water infiltration modelling, damage and cost assessment, etc. According to the outputs of these processes, they are transferred to PL for presentation to the user or requesting further data inputs. On the other hand they may be sent back to DAL for export or storage purposes.

Finally, PL in this architecture contains the User Interface (UI) of the system that allows for the necessary interactions with its users; i.e. capturing user inputs or presenting him/her with the outputs of the [lower level] modules. For the purpose of implementation and efficient use of other existing platforms, the PL spans across three different software packages; i.e. the developed UI of the system, ESRI ArcGIS platform, and the ANSYS (2009). These will be discussed further in Section 4.

While the components of each layer are permitted to interact with each other, the hierarchy of layers only allows access to functionalities at the lower levels and not other way around.

4. DEVELOPMENT

The implementation of the prototype system was mainly according the Object Oriented principles and the Microsoft .NET technologies. This section presents the developed system and its functions.

According to the envisioned functions of the system in Section 3.2 and the guidelines provided by the framework, the workflows of the system were designed and implemented. These workflows are classified into four functions; the *data import, damage assessment, risk calculation,* and *exporting the results* functions that are explained shortly. Corresponding to these functions, the main UI of this tool, as illustrated in Figure 3, consists of four main tabs and was designed using Windows application forms.

The first tab provides tools for users to import the required data (i.e. elevation, property data, flood data, building information and the construction costs of its components) into the system database. The second tab (physical damage assessment) enables users to initiate the execution of the water infiltration modelling as well as those pertinent to the assessment of damage on building components.

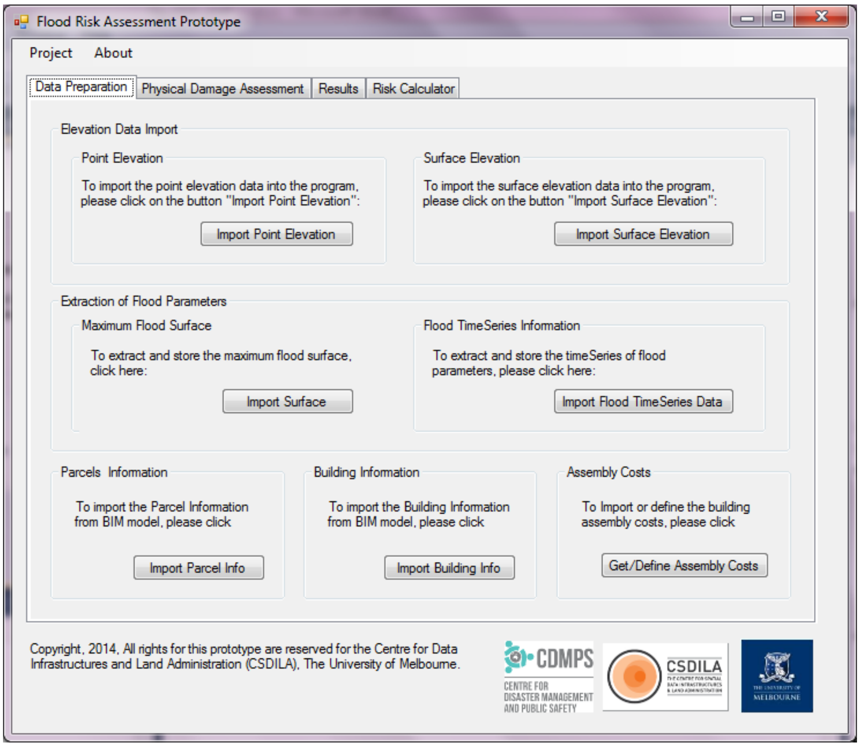


Figure 3: User Interface of the prototype system

While the fourth tab (risk calculator) provides tools for calculation of the flood risk of the building, the "results" tab allows users to export the outputs of the damage analysis to a suitable format; i.e. tabular (using CSV files) or 3D ShapeFiles to be visualised and queried in 3D GIS software. An ArcGIS platform, in particular the ArcMap and ArcScene tools, were used to provide 2D/3D interactive visualisation of (a) the flood parameters around the building and, (b) the damage to the building assemblies. In addition, tools are provided to the users to query and inspect the results in tabular form and for different phases of the analysis.

As discussed earlier in this section, four general functions are considered for the prototype system. The details of each and their implementation in the prototype are discussed here.

Data import

The data import function includes a set of functionalities across all layers of the platform for bringing together the required data (e.g. flood and building information) from various sources for use in the system. The data import is complex and requires some degree of prior data preparation and processing. For this purpose, in addition to the prototype system, a number of additional tools via making use of open source technologies were developed to perform these tasks for a variety of required data types. For example, a toolbox was developed in the ArcGIS platform to process the flood parameters from the acquired output of the flood simulation in one of the most popular hydrodynamic modelling software, the DHI's MIKE 21. The underlying processes refine and manipulate the flood parameters and generate two sets of outputs including the 3D point and surface representation of the distribution of flood parameters. Similarly, building information in IFC files could be extracted using a complex workflow in a tool for that purpose.

Following the pre-processing of data, each set of requirements is imported into the database via import modules and the developed UI in the system. An example of the import process for the point distribution of flood parameters is presented in Figure 4 using a Unified Modelling Language (UML) Sequence diagram. The pre-processed points are used as inputs to the system and are parsed using the CatFood open source project. They are then stored in the XML database in a Geographic Markup Language (GML) 'Coverage' concept, the gml:multiPointCoverage.

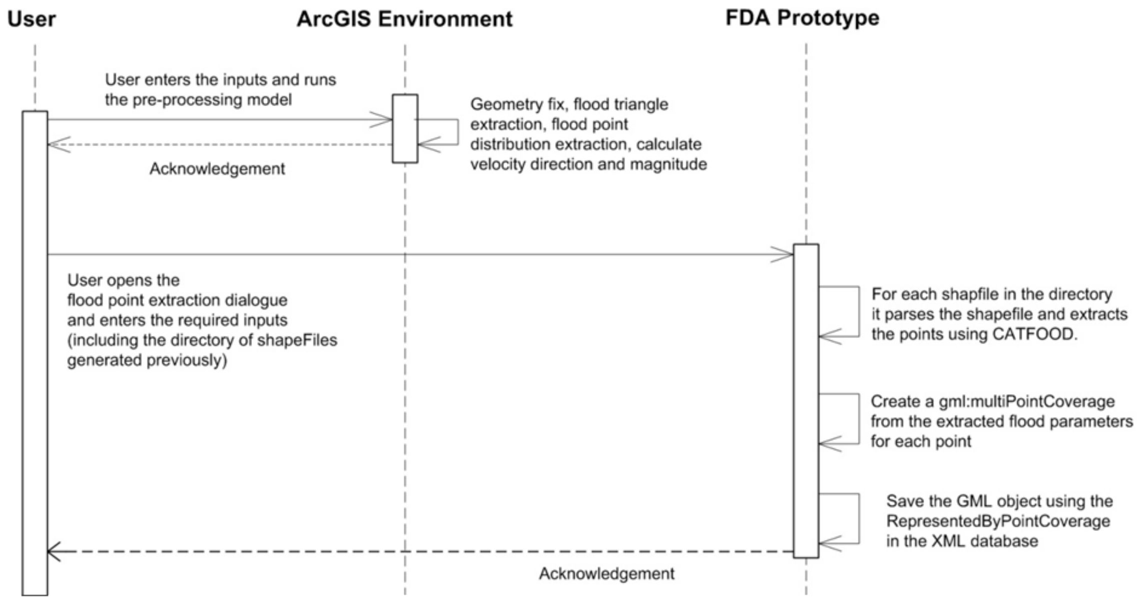


Figure 4: pre-processing and import process of flood parameters point distribution

In addition to the data import functions, complex internal processes were designed to spatially link the imported flood parameters and those building components that can be affected by the floodwater impacts. The system allows the prepared data to be saved as part of a particular scenario and to be loaded at any time for analysing the flood damages and risks to the building.

Damage assessment and risk calculation

The damage and risk assessment modules as well as the flood infiltration modelling are designed to estimate the physical impacts of floods to a given building. As illustrated in Figure 5, following the "loading" process of data and activating relevant modules in the DAL, the physical damage to each building component is evaluated in two overall steps. For individual time steps with fixed duration, first the infiltration through wall panels, weep holes, air bricks, windows, doors and sliding doors are calculated and accordingly, the water depth inside and outside of the building is estimated for that time step. A graphical representation of these water depths is communicated to the user in the real time using the user interface of the system. Next, on the basis of the identified engineering models and the depth of water for the inside and outside of the house, the physical damage is estimated.

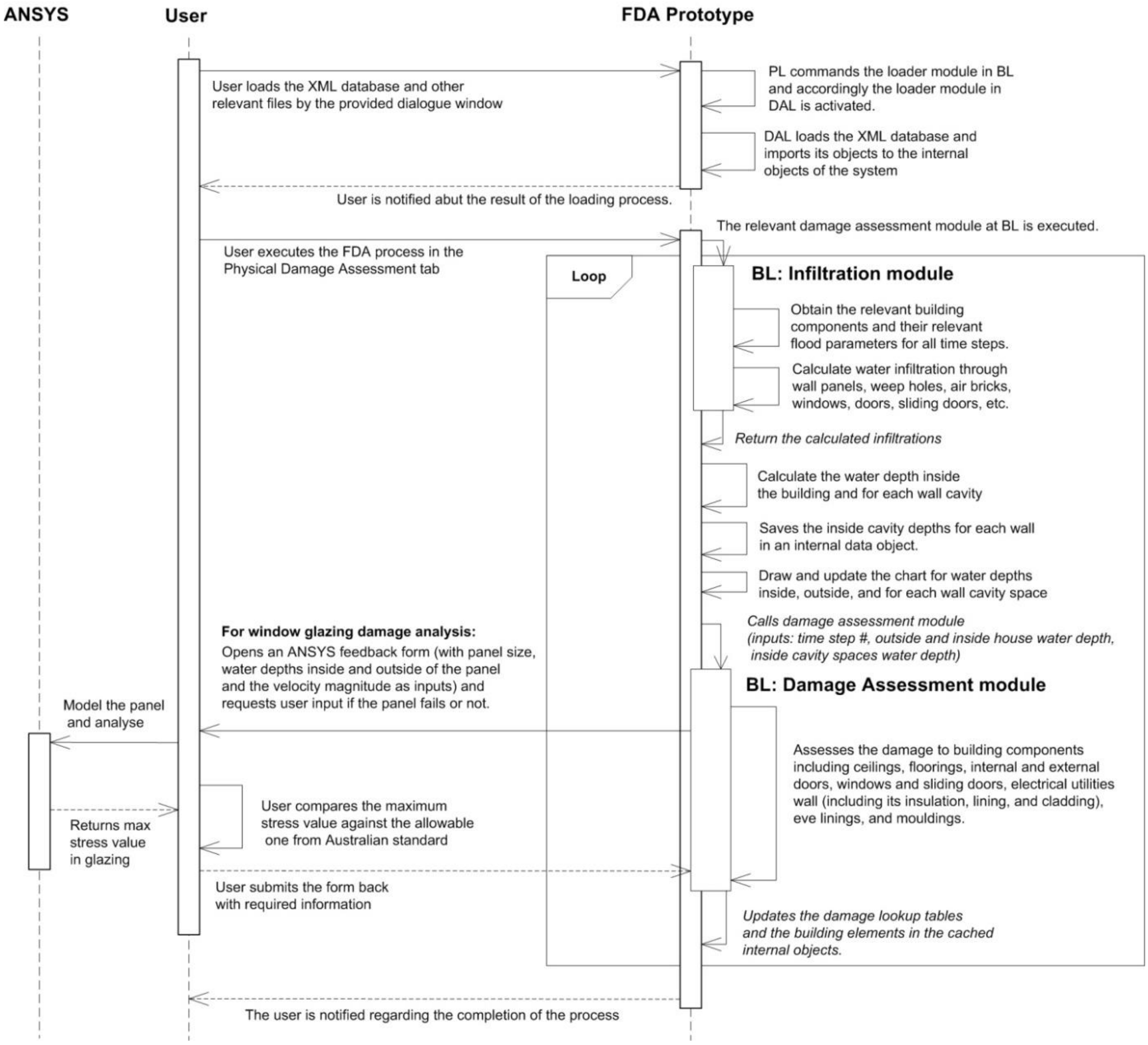
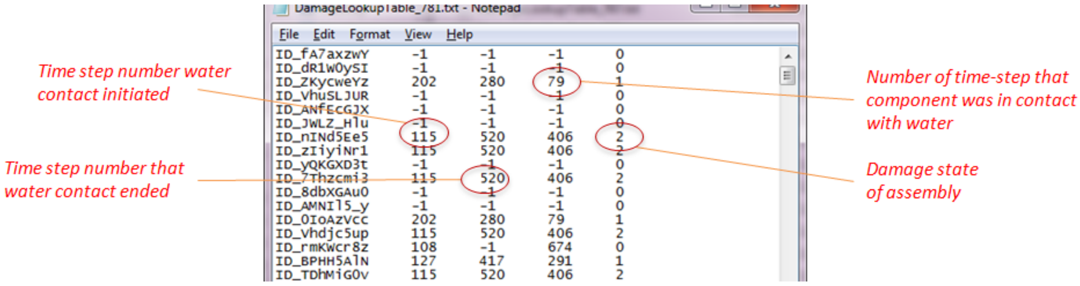


Figure 5: Water infiltration modelling and damage assessment workflow in the system

The system contains internal objects called "DamageLookupTables" in which the water depths, as well as the water contact duration and damage status of building components for each time step is maintained. Figure 6 illustrates an example of DamageLookupTable which can be presented to the user following the completion of the analysis.



ID_fA7axzwY	-1	-1	-1	0
ID_dR1W0ySI	-1	-1	-1	0
ID_ZKycweYz	202	280	79	1
ID_VhuSLJUR	-1	-1	-1	0
ID_ANfEcGJX	-1	-1	-1	0
ID_JWLZ_Hlu	-1	-1	-1	0
ID_nINd5Ee5	115	520	406	2
ID_zIiyiNr1	115	520	406	2
ID_yQKGXD3t	-1	-1	-1	0
ID_7Thzcmi3	115	520	406	2
ID_8dbXGAu0	-1	-1	-1	0
ID_AMNI15_y	-1	-1	-1	0
ID_0IoAzVcc	202	280	79	1
ID_Vhdjc5up	115	520	406	2
ID_rmKWcr8z	108	-1	674	0
ID_BPHH5AlN	127	417	291	1
ID_TDhMiG0v	115	520	406	2

Figure 6: An example of DamageLookupTable

While the damage assessment to the majority of the building components is performed automatically in this prototype, the evaluation of damage to window glazing panels should be performed manually at this stage of development. For this purpose, a simplified finite element model of a glass panel with adjustable dimensions was constructed in ANSYS - a powerful finite element modelling tool - which by varying the water levels on its sides, the maximum stress in the panel could be analysed (see Figure 7). This stress could be compared with the suggested maximum allowable stress in the Australian standards, and the failure of window/door glazing panels is evaluated. The result is obtained from the user and via a designed UI that appears during the analysis whenever such feedback is required.

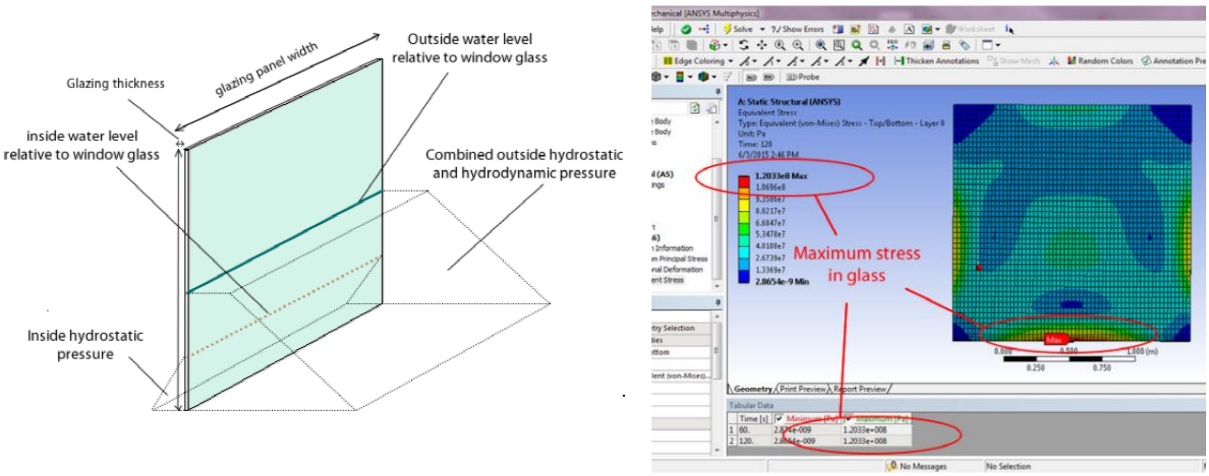


Figure 7: conceptualising water loads on glazing panel (left); modelled stress in panel in ANSYS

Following the calculation of physical damage to all buildings elements for the duration of the flood, using the estimated damage status of each assembly and its replacement cost, the damage costs for the building and its individual components can be estimated. Furthermore, the probability of occurrence of the flood and the quantified damage can be used to estimate the risk to a given building. These risk calculation guidelines are provided in the designed framework (refer to Amirebrahimi et al., 2015b).

Data export

The results of the damage assessment can be exported to 3D ShapeFiles for visualisation purposes, or to tabular format for showcasing the details of the damage. The workflow of the former export type is presented in Figure 8 as an example. By selecting the "Write to Shapefile" option in the third tab of the main UI, the exporter module in BL is activated. For every building element type, the geometry of individual objects and their extracted attributes, using the extended functionalities of CatFood in DAL, these are exported to ShapeFiles in ESRI Multipatch format. On the other hand, the flood parameters (their point or surface representation) are written to Shapefile and along with the building files and other generated outputs, these are stored in the designated output folder.

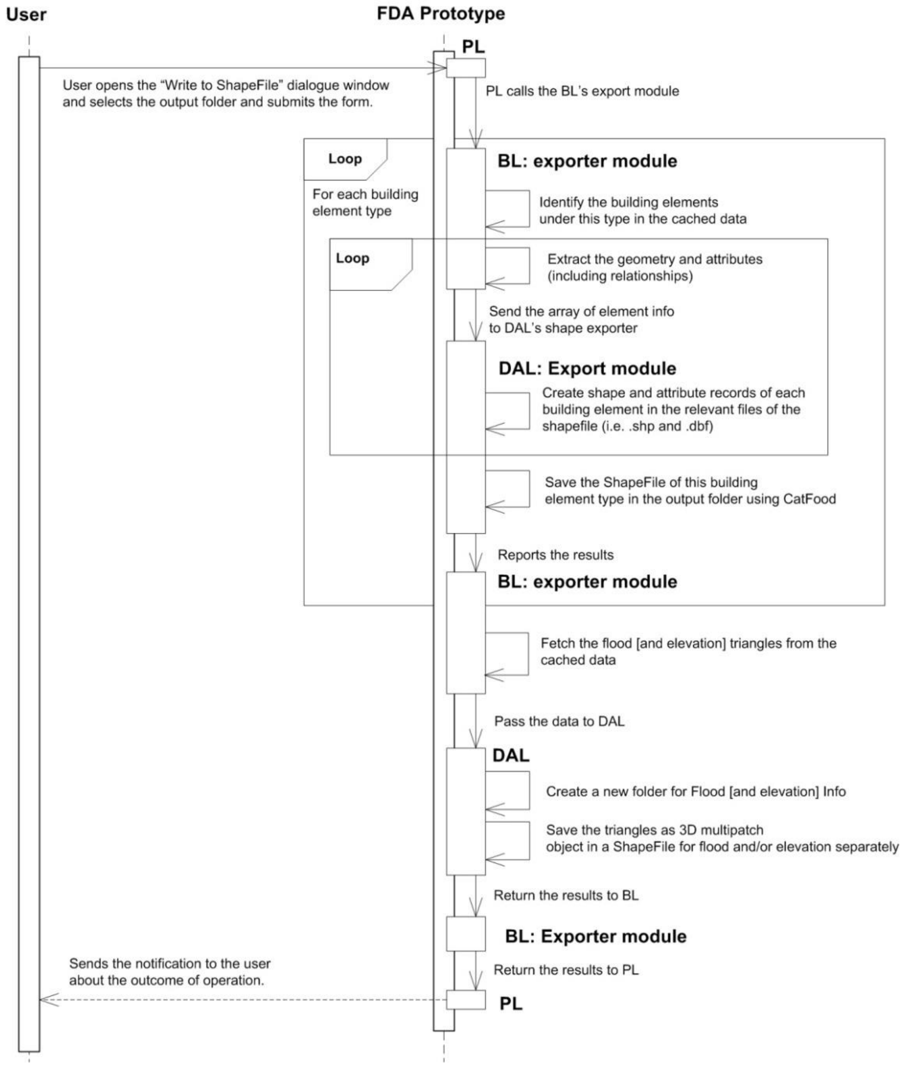


Figure 8: Process of exporting the results to 3D GIS format

The exported files can be opened using ESRI ArcScene, added to a map as a layer and be styled and colour-coded according to their damage states and the preference of the user. Furthermore, users can inspect the details of the components and their damage using the built-in "identify" tool in this software. The exported tabular Comma Separated Value files (CSV) can also be presented to the user via Microsoft Excel (or similar software packages) for further inspection of the details of building damage.

5. EVALUATION

The evaluation of the prototype system included two phases. The first phase is the internal validation to confirm it can produce effective results for decision making in real life applications; and the second phase tests the prototype in a real life planning decision making scenario.
The validation of the framework was undertaken according to the criteria defined in a method called "Face Validity" (Eddy et al., 2012). For this purpose, a series of structured face-to-face interviews with academics and practitioners in the field were conducted to validate the structure, flow of analysis and the data sources of the framework and the tool. The analysis of the feedback from the participants showed that the structure, logic and the processes used for water infiltration modelling and damage assessments were designed effectively. In addition, participants were presented with the outputs of the tool produced for a real scenario and confirmed that the system can reasonably estimate the flood damage and risk to a building and effectively communicate this information to the user.

In addition, a case study was conducted in collaboration with Maribyrnong council and the Melbourne Water to assess the flood risks to a proposed single-storey brick veneer house (the most common construction type in Australia) in the Maribyrnong area. Following the acquisition of the required data from their relevant authorities, the BIM of the building was developed and a seven-day long 1-in-100-year flood in the area was simulated using MIKE 21 software. Based on the analysis of the imported data, the case study results showed that flooding around the building could be visualised for different time steps in both 2D and 3D. The results are illustrated in Figure 9 and Figure 10.

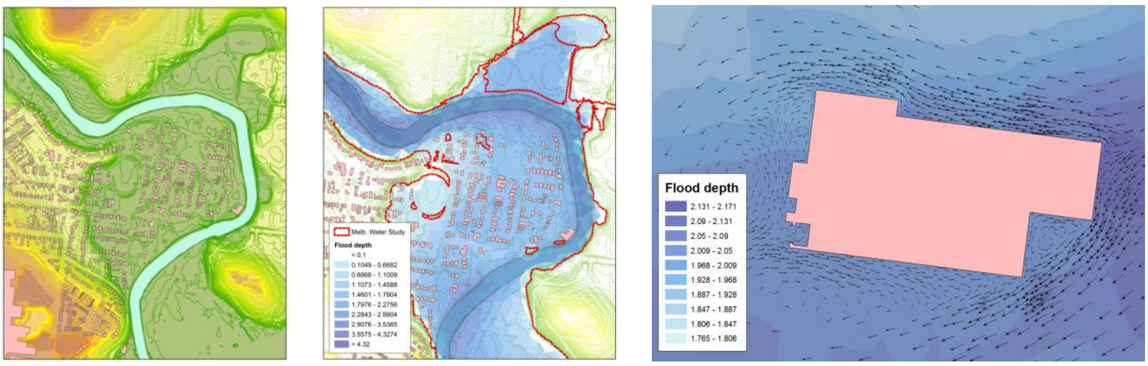


Figure 9: Case study area in Maribyrnong (left); 2D visualisation of the flood extent in the area (middle); Visualisation of the depth and velocity of flood around the building in ArcGIS (right).

A thorough explanation of the case study is presented in detail in Amirebrahimi et al. (2015b). The analysis of the damage for the building in this study showed that while no major structural damage was sustained by the building, it still suffered from approximately AUD$51,000 damage from water contact impacts. This number is the sum of damage costs to individual elements of the building. In addition, these damages were visualised in 3D in ESRI ArcScene and, as Figure 11 illustrates, could be interactively queried. Furthermore, the flood risk of the building was calculated as *risk = hazard x vulnerability = 0.01 x 51000 = 510.*

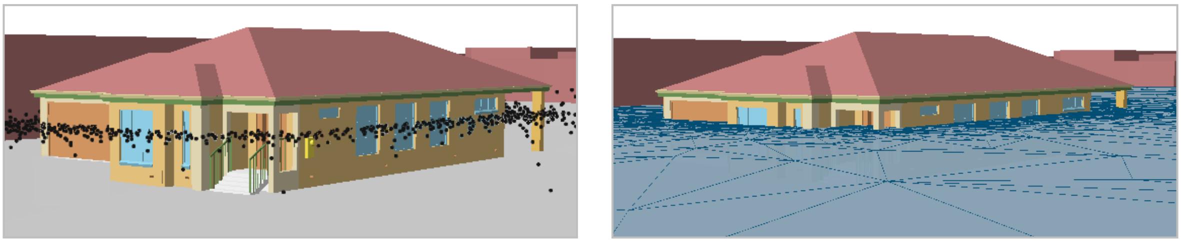


Figure 10: Representation of flood around the building using 3D points (left) and (right) surfaces

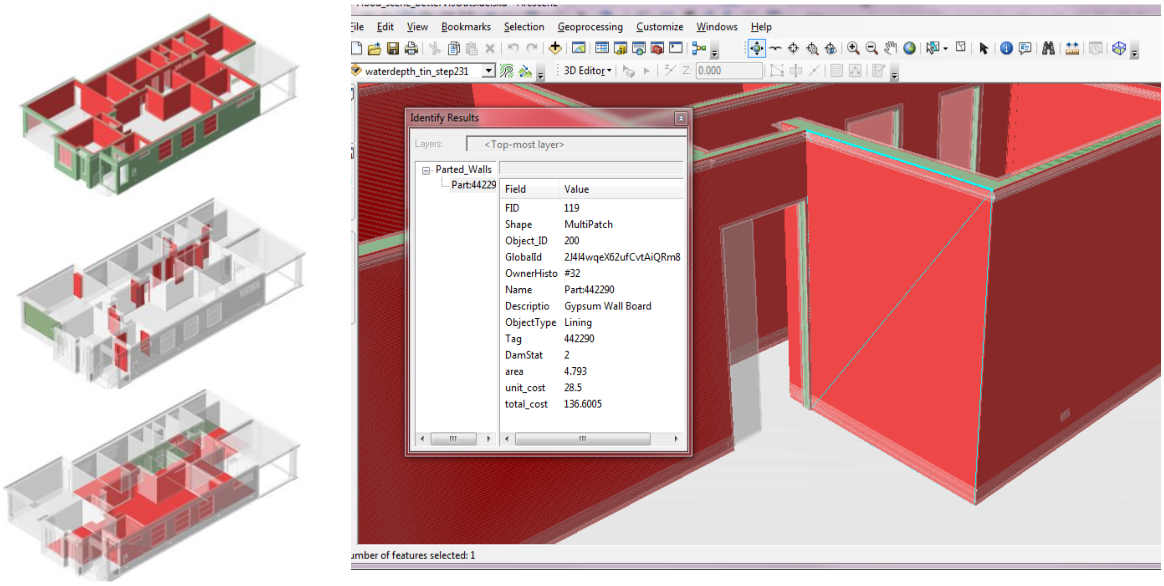


Figure 11: Three-dimensional visualisation of damaged walls (top left), doors (middle left), and flooring (bottom left); Querying the damaged wall linings in ArcScene (right)

Additional face-to-face interviews with a number of staff in the Department of Building and Planning in Maribyrnong Council underlined the benefits of this tool to the planning and land development process. It was highlighted that such decision support tool can be used for evaluation of buildings prior to their construction for issuing planning and building permits. On the other hand, the current practice in Maribyrnong Council includes the acquisition of land with high flood risk so that no development can happen in them. During the evaluation of the tool it was underlined that by employing the proposed tool in the spatial planning process and testing the strength of the proposed developments, the council can investigate opportunities to utilise this land in a productive manner given that the flood risk can be accurately estimated with the developed tool. The feedback also indicated that in situations where disputes exist between owners and council regards to rejection of a particular proposal due to flood risks, the 3D visualisation provided by the tool, as oppose to difficult engineering language, could lead to better comprehension of the risks by the owner.

6. CONCLUSIONS AND FUTURE WORK

This paper presents the design and development of a decision support system for detailed assessment and 3D visualisation of flood damage and risk to buildings. The tool was implemented using a multi-tier and modular architecture that not only increases its flexibility but also facilitates the extension of the system and integration of additional modules without the need for altering its core components. Via provision of the mode, location, and cost of damages and risks at the building level, this system can effectively be employed to detect non-conforming buildings and facilitate the decisions for increasing the resilience of proposed developments in flood prone areas at their planning stages. A two-fold evaluation of the prototype system indicated that it is able to produce useful outputs that assists in effectively communicating the building flood risk to a range of technical and non-technical decision makers.

This should be bear in mind that the proposed tool is designed for and accordingly best applicable to new buildings at their planning stage. This stems from the underlying assumptions in its development and by not taking into account a number of effects like aging, adverse impacts from weathering or previous events which may influence resistance of buildings. Therefore, the use of the proposed tool for existing buildings should be undertaken with caution. For improving the proposed system, future work should consider taking into account the uncertainties of the abovementioned factors; optimising the algorithms and fully automating the system. However, the design of the prototype system has been shown to meet the general needs for the assessment and communication of damage/risks to building in the land development process. Since users in different organisations may have specific needs or preferences, a systematic requirement analysis for each organisation and development of an organisation-specific system is envisioned and proposed as future work. In a similar way, for a more complete evaluation, the other use cases (in other domains besides planning) should be tested. Lastly, the adoptability of this system in the industry must be evaluated and questions such as "*How the system would fit in and benefit the business processes of those organisations?*" should be answered.

ACKNOWLEDGEMENTS

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