A Planning Decision Support Tool for Assessment and 3D Visualisation of Flood Risk to Buildings

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Summary

Following the 2010-11 floods in Queensland and Victoria, the statutory planning acts as well as the Australian Building Code were modified to put a special emphasis on increasing the flood resistance of new developments in flood-prone areas and ensuring their flood resilience. In the current practice, depending on the local government planning workflows, each development in flood overlay zones is either assessed by the council itself or referred to respective referral authorities. The "Freeboard" - the maximum allowable water depth above habitable floor-level - is the most acceptable and commonly employed tool for evaluating the proposals in Australia. It however, does not take into account the flood resilience of design and the materials of the building. On the other hand, the current risk assessment tools are either limited for estimation of buildings flood risks or do not account for unique responses of buildings against flood actions. The shortcomings of the current methods may hinder evidence-based decisions by a range of decision makers for effective design of the buildings or employing of mitigation measure for ensuring their flood resilience.

This paper provides an overview of a designed framework and a decision support tool for a detailed assessment of flood risks to proposed buildings. This tool, in support of the current planning needs, allows for the identification of type and the monetary cost of potential flood damages at building's individual component level. In addition, it generates a visualisation of damages that can be queried in an interactive 3D environment. The evaluation of this framework using a real case study showed that it can facilitate decision making for a range of technical and non-technical decision makers for a more resilient and sustainable building design in the planning and development process.

Introduction

Floods are the costliest and most frequent natural disasters in Australia and around the world (Jha, Bloch, & Lamond, 2012). The lessons learnt from the recent floods have underlined the limitations of management of such hazards via sole focus on containment strategies using flood walls, levees, or other structural measures (Birkmann et al., 2013; Merz, Kreibich, Schwarz, & Thieken, 2010). Accordingly, modern flood management techniques adopt Flood Risk Management (FRM) as their central framework. Via 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 at different levels of the community.

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, Giron, Ernst, Hecq, & Pirotton, 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 (Dewals et al., 2008; Grundy, Thurairaja, & Walker, 2005). 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 (ABCB, 2012; Van de Lindt & Taggart, 2009). Despite these requirements, the Australian and New Zealand construction standards provide little 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 (Becker, Johnstone, & Lence, 2011; CSIRO, 2000). 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 (Lamond & Proverbs, 2009; Matthew, 2005).

Amirebrahimi, Rajabifard, Mendis, and Ngo (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). It provides necessary guidelines for detailed assessment and a 3D visualisation of flood risks to a building and according to 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.

Methodology

The development of the flood risk decision support system was undertaken according to the principles of "prototyping" (Nunamaker, Chen, & Purdin, 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 research 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.

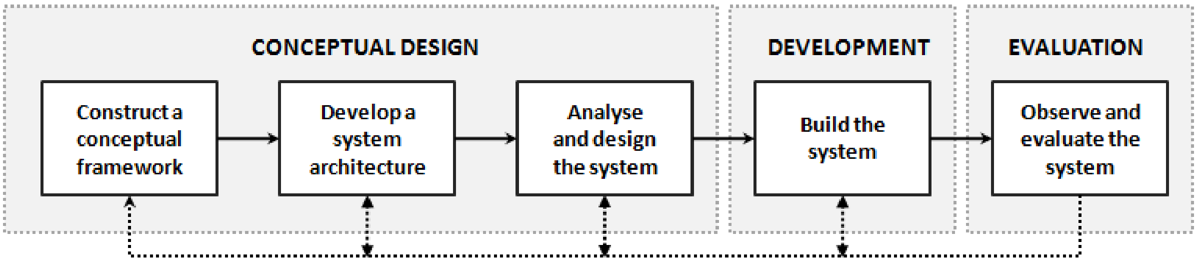

Figure 1: Prototyping methodology (modified from Nunamaker et al., 1990-91)

Conceptual design

The conceptual design of the tool, as illustrated in Figure 1, includes three steps; i.e. construct a conceptual framework, develop system architecture, and analyse and design the system.

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 put to account for water infiltration computation that was identified as a prerequisite for many of these damage assessment processes. Via 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; i.e. *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 GIS systems. For the details of the framework and the data model reader is referred to Amirebrahimi, Rajabifard, Mendis, and Ngo (2015a); Amirebrahimi et al. (2015b).

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 (for each time sep 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 composed of four layers; i.e. *Data Layer (DL)*, *Data Access Layer (DAL)*, *Business Layer (BL)*, and *Presentation Layer (PL)*.

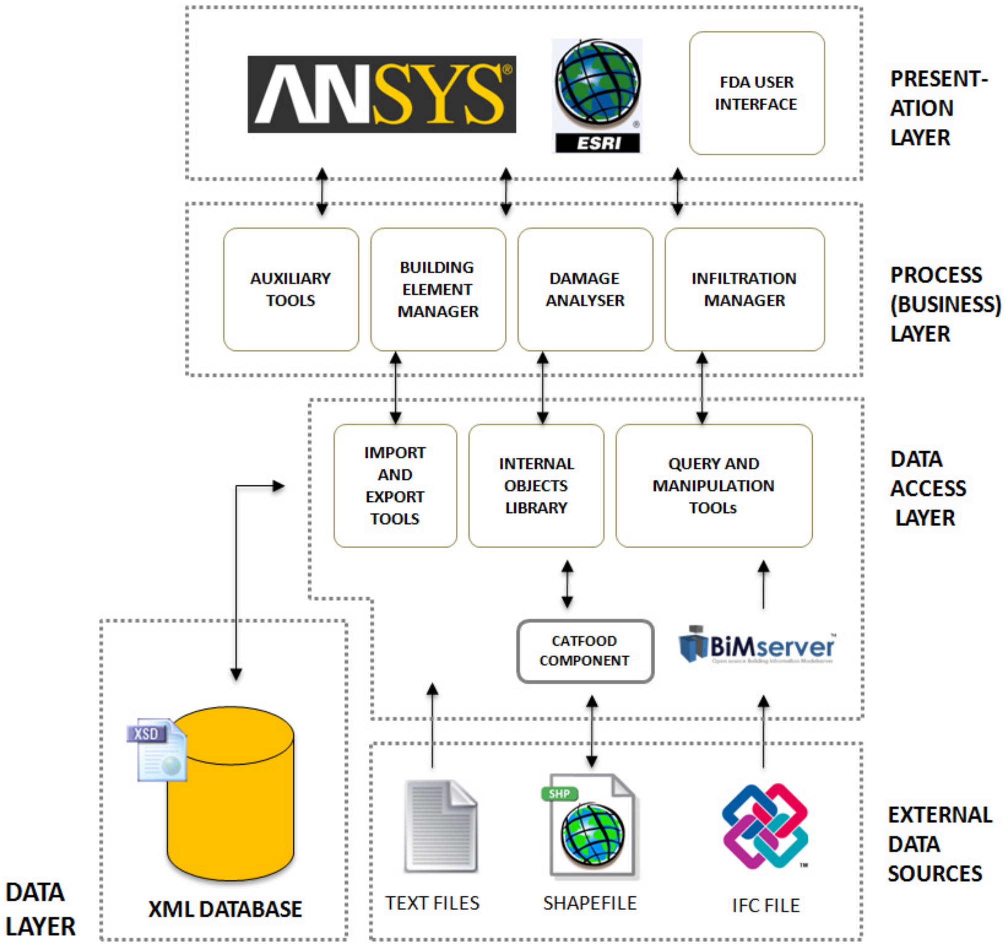

Figure 2: Flood risk assessment prototype system architecture

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 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 (2014) were used for implementing these modules.

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, Presentation Layer 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 further discussed 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.

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 *data import, damage assessment, risk calculation,* and *exporting the results* which 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), on the other hand, enables users to initiate the execution of the water infiltration modelling as well as those pertinent to the assessment of damage on building components.

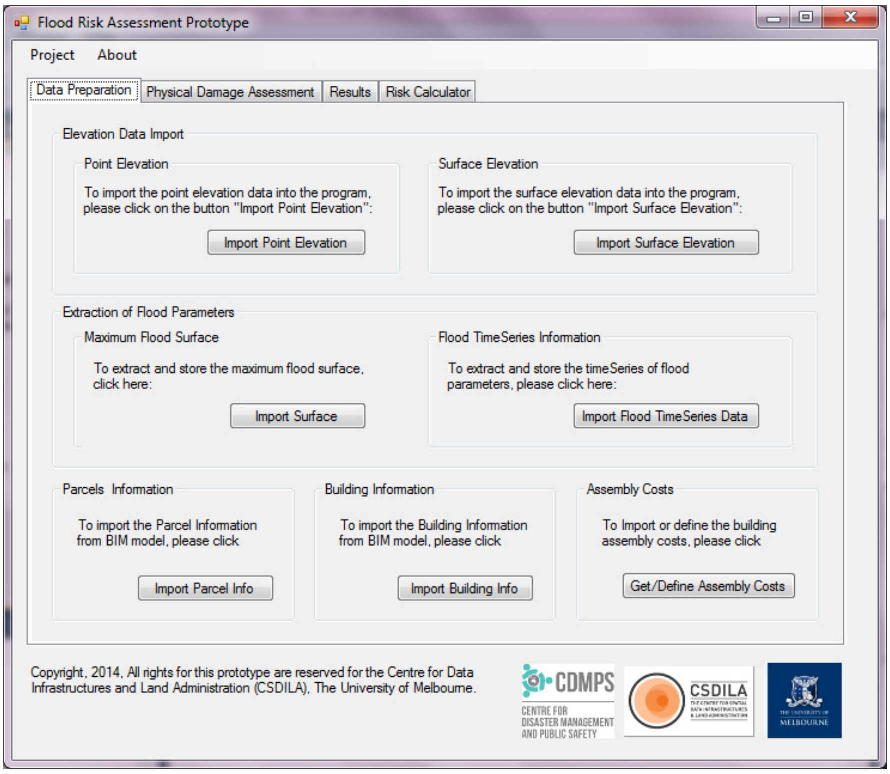

Figure 3: User Interface of the prototype system

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 analysis to a suitable format; i.e. tabular (using CSV files) or 3D ShapeFiles to be visualised and queried in 3D GIS software. ArcGIS platform and particularly 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 in here.

Data import

The data import 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, via use of open source technologies, a number of additional tools were developed to perform these tasks and for different required data. For example, a toolbox was developed in the ArcGIS platform to process the flood parameters from the acquired output of the flood simulation in DHI MIKE software. The underlying processes refine and manipulate the flood parameters and generate two sets of outputs including the 3D point and surface representation of flood parameters distribution. Similarly, building information in IFC files could be extracted using a complex workflow in a developed tool.

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 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.

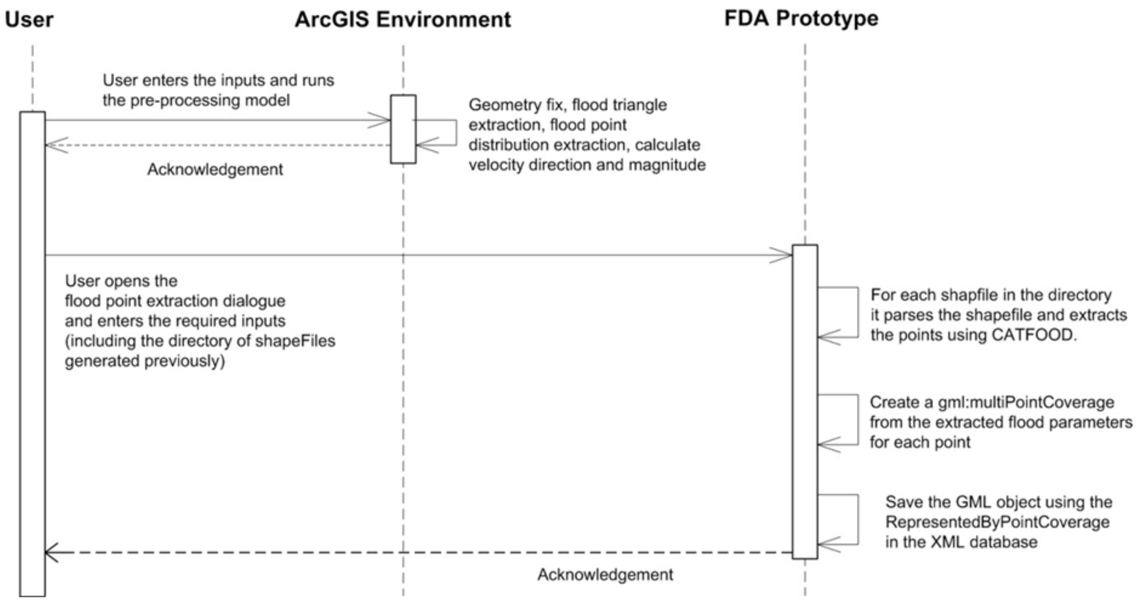

Figure 4: pre-processing and import process of flood parameters point distribution

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.

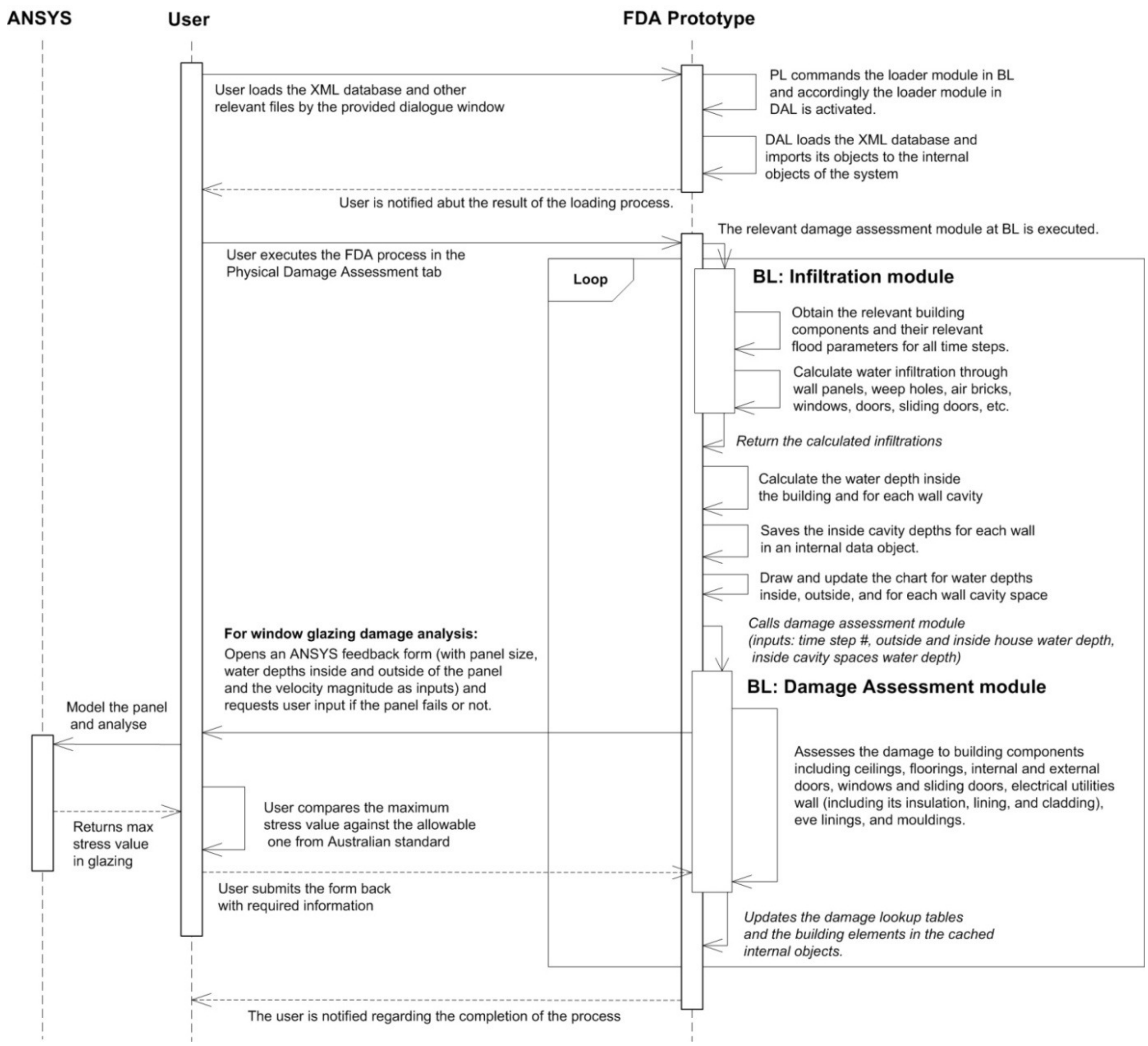

Figure 5: Water infiltration modelling and damage assessment workflow in the system

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 DamageLookupTables which can be presented to the user following the completion of the analysis.

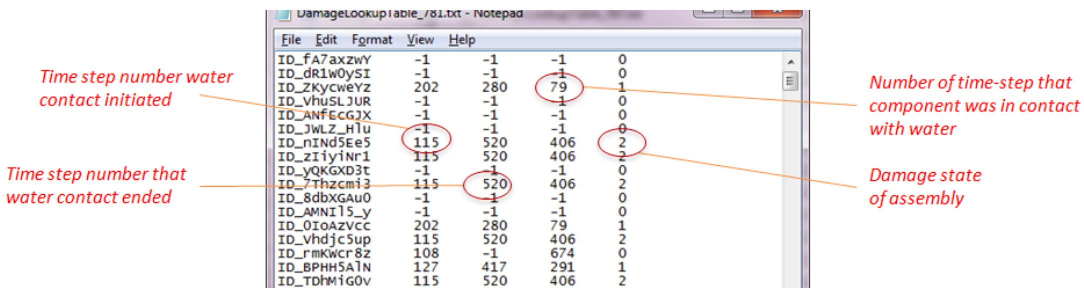

Figure 6: An example of DamageLookupTable

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 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.

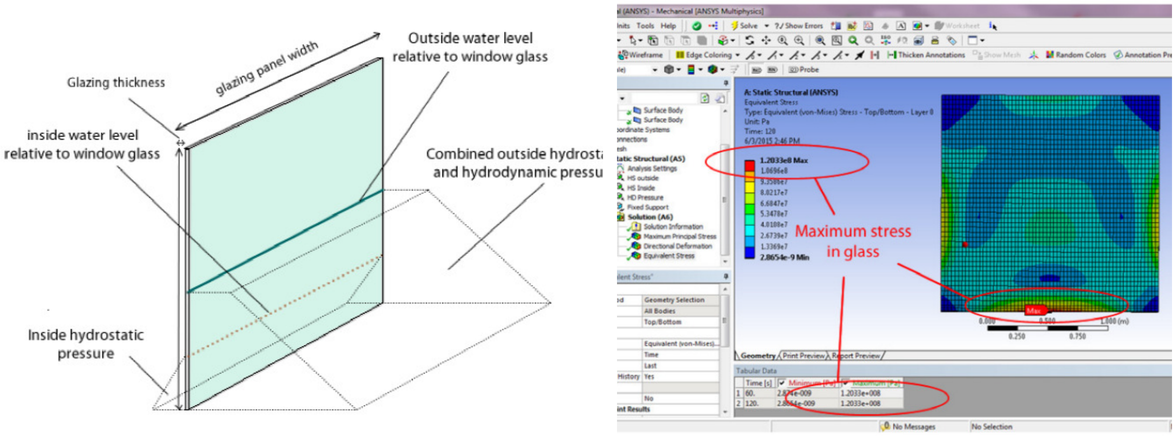

Figure 7: conceptualising water loads on glazing panel (left); modelled stress in panel in ANSYS

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, individual object's geometry and attributes extracted and via using the extended functionalities of CatFood in DAL, exported to ShapeFiles and 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, is stored in the designated output folder.

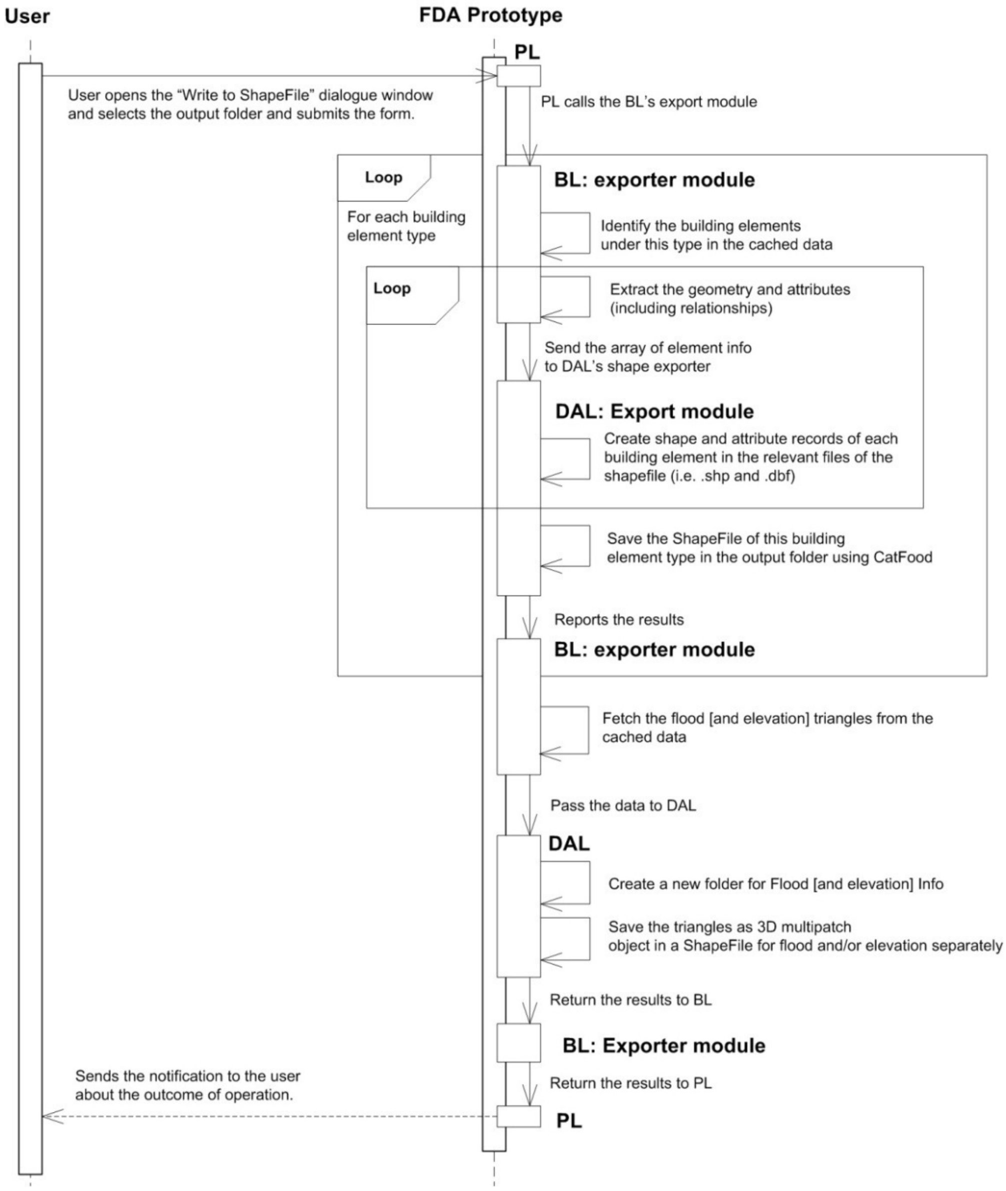

Figure 8: Process of exporting the results to 3D GIS format

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. On the other hand, the exported tabular CSV files can be presented to the user via Microsoft Excel (or similar software packages) for further inspection of the details of building damage.

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.

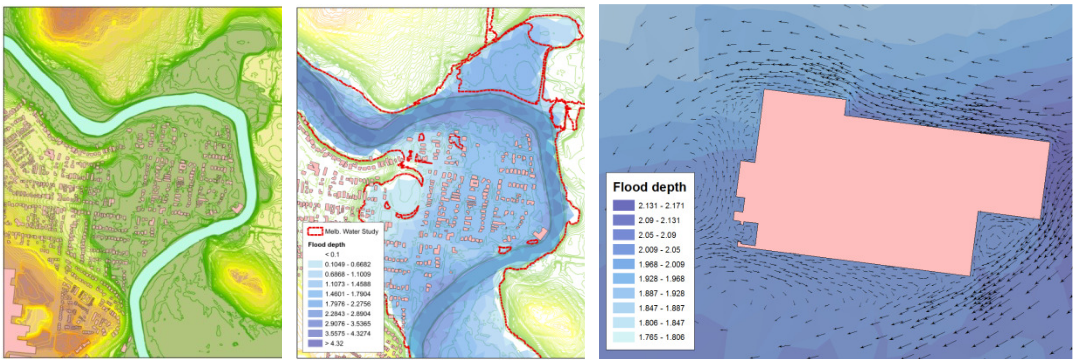

Figure 9: Case study area in Maribyrnong (left); 2D visualisation of the flood extent in the area (middle); Visualisation of the depth and velocity of flood around the building in ArcGIS (right).

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.*

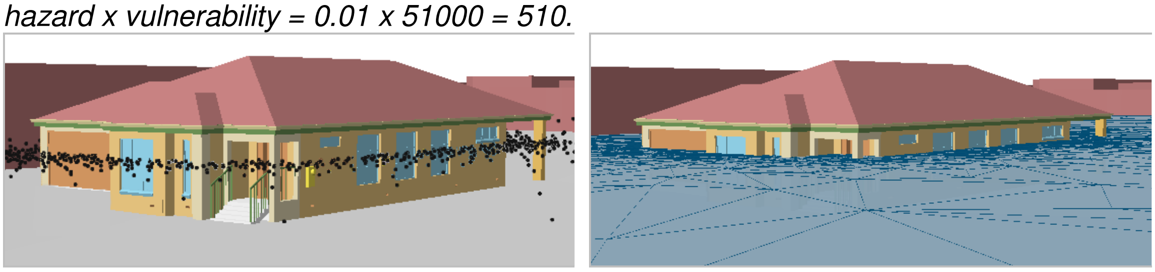

Figure 10: Representation of flood around the building using 3D points (left) and (right) surfaces

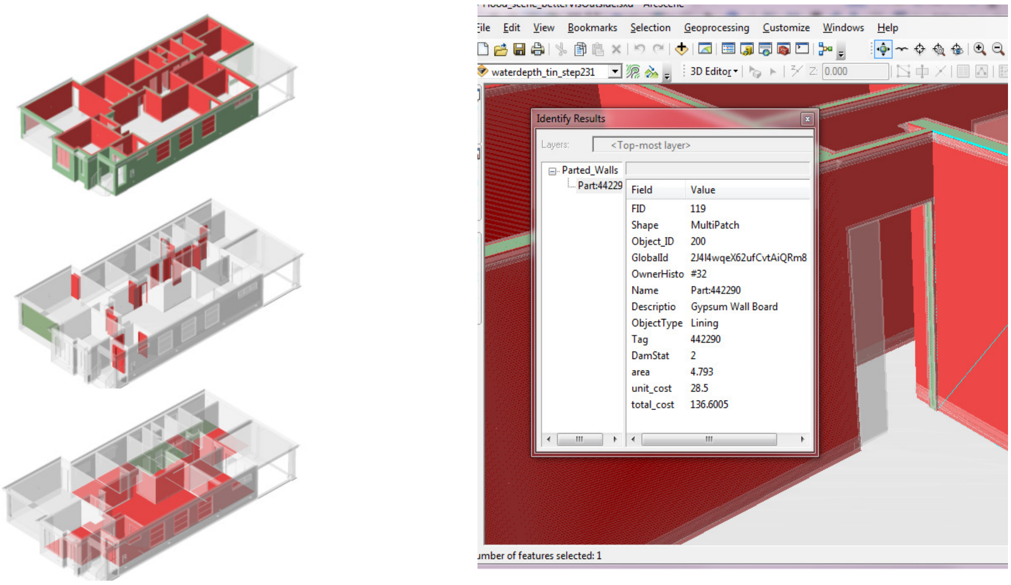

Figure 11: Three-dimensional visualisation of damaged walls (top left), doors (middle left), and flooring (bottom left); Querying the damaged wall linings in ArcScene (right)

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.

Conclusions and future work

This paper presented 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 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 sound outputs and effectively communicate these results to a range of technical and non-technical decision makers.

For improving the proposed system, future work should consider optimising the implemented algorithms and fully automate the system. On the other hand, the design of the prototype system was according to 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, therefore, 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, the adoptability of this system in the industry must be evaluated and questions such as "*Would deploying and the use of system improve productivity in the organisation?"* should be answered.

Acknowledgements

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