

# Flooding of an ancient ship during the shipwreck

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**Abstract:** Shipwrecks are the remnants from the past that contain the story about the ship, sailors, cargo, and some aspects of the world of that time. A shipwreck also acts as evidence of the event, usually tragic, that brought the ship's life to end. Depending on the evidence from the archaeological site, various reasons for the sinking of the ship can be examined. State-of-the-art engineering tools may be used to simulate the events leading to a shipwreck. In this article, numerical modelling and analysis are applied to calculate flooding time until the loss of buoyancy of the idealised ancient vessel, which precedes the inevitable sinking. The paper aims to assess the questions about how much time is needed in various scenarios for the sections of an ancient ship to get flooded, and how the internal design of the ship influences the flooding time.

**Keywords:** ancient ship, shipwreck Finite Element Modelling, Fluid-Structure interaction, flooding, 2D analysis, ICFD

## 1. Introduction

Shipwrecks of ancient ships all over the world witness the extensive sailing history of mankind. Transport of people and goods was never without risks. Ancient sailors relied on available resources in shipbuilding and seafaring and were facing dangers such as bad weather, uncharted waters, ship structural damage occurring due to various reasons etc. One of the serious problems was the flooding of the ship. It could have happened for various reasons, such as the action of the storm waves, collision or contact with some rock or object in the water, leaking due to poor sealing of seams between planks and so on. Minor penetration of water in the ship's hull was normal and was manageable by the crew. However, the excessive penetration of water was a serious problem, often leading to the loss of ships and cargo, and sometimes human lives.

Flooding is extensively studied in contemporary naval architecture, and different flooding scenarios are examined to secure ship survival in the case of water ingress. Commonly, watertight bulkheads and compartments, as well as openings and passages, are designed to minimise the effects of flooding, or maximise the time available for evacuation or salvage operations. On the other hand, forensic analysis of historic ship flooding is rarely performed using state-of-the-art engineering tools. Stettler and Thomas (2013) performed flooding and structural forensic analysis of the sinking of the RMS Titanic. They modelled progressive flooding, using GHS software, which seeks the static equilibrium between the weight of the vessel and its buoyancy, and considers the change of internal liquid-free surface. In subsequent analysis, authors performed a structural analysis of the complete FEM model of the Titanic.

The fast simulation approach, based on potential theory, was done by Ancafora *et al.* (2017). Even though it predicted with reasonable accuracy the flooding volume of water, the mathematical model did not predict roll motion and behaviour under waves in a satisfactory way. Rudan and Radić Rossi (2017) presented a two-stage numerical simulation of the floating, flooding and sinking of an ancient ship. Arbitrary-Lagrangian-Eulerian (ALE) method was used to simulate the floating of the 2D ship model with cargo in the waves. Flooding was modelled as a simple loss of buoyancy over time. In the second stage, motions of the surface ship were applied to the structural model with cargo, and the simulation was performed until the ship rested on the seabed.

A more common way to study the flooding process is by the application of the Finite Volume Method. Gao *et al.* (2011) performed computational fluid dynamics (CFD) analysis of a flooded Ro-Ro ship, which showed that rolling frequency decreased over time, but mainly from internal sloshing, and less from flooded water. Further dynamics of ship flooding were done by Khaddaj *et al.* (2012), by conducting physical experiments of a scaled compartment,

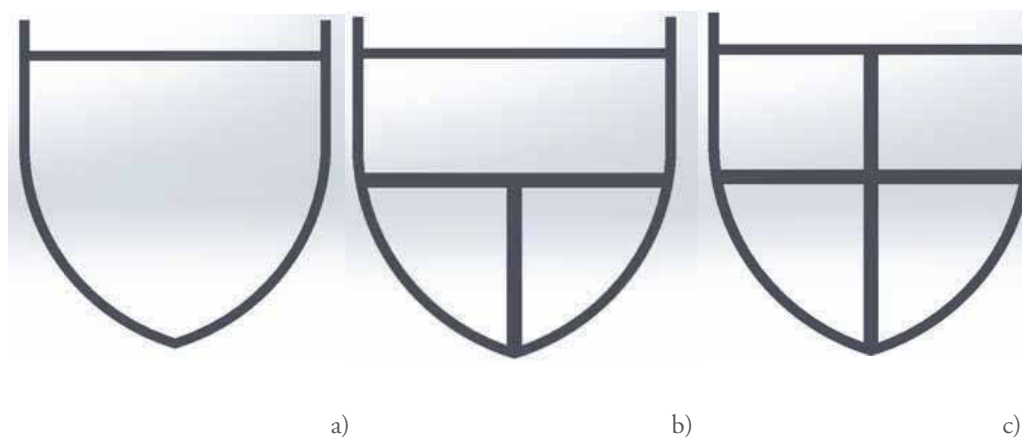
with the main goal of investigating water and air behaviour during flooding. Abrupt flooding of ships with multiple compartments was done by Zhang *et al.* (2019) by using the Finite Volume Method, and air compressibility was introduced. While the study captured very advanced physical behaviour, such as air compressibility and formation of bubbles, simulations lasted over 161 hours.

This article aims to examine the flooding process for some idealised internal designs of ancient ships, as well as different dimensions, and different locations of hull ruptures. Ancient ships were capable of long-distance sailing while withstanding rough weather conditions. Structural material used in ancient shipbuilding was usually wood, which did not have large safety margins, and often suffered from structural damages. This led to openings in the hull sections, and consequently to the sinking of the ships. The goal of the study was to investigate how much time was needed for the loss of buoyancy and sinking, and if the internal design of the ship influenced greatly the flooding time. Finite Element Modelling was used, accompanied by the Fluid-Structure Interaction method, so the fluid could be modelled and incorporated into the analysis.

## 2. Numerical model

### 2.1. Geometry

The ship's mid-section was extracted using 3D modelling software, and a 2D surface model of the ancient ship was created. Both ships' outer width and height are equal to 3 meters with additional added taffrail that captures a water-on-deck effect equal to 0.1 meters in height. The internal geometry directly influences the ship's stability and flooding time. As an ancient ship's internal geometry is difficult to understand without well-preserved ship remains, the most common arrangements of ship compartments are used. Those are: ship with one compartment (Fig. 1a), ship with three compartments (Fig. 1b) and ship with four compartments (Fig. 1c). To better understand the difference between flooding time for three different ships, structure density was adjusted so all three ships weigh equally 3.5 tonnes.



**Fig. 1** Internal ship design: a) One compartment; b) Three compartments and c) Four compartments (author: Š. Sviličić)

### 2.2. Fluid-structure interaction

Analysis of a fluid environment requires dividing the fluid into basic computational elements, or finite elements. The interaction and iterative solving of the elements is a complex process which requires significant computational resources and high simulation time. In order to decrease simulation time, 2D analysis was performed. For solving ship flooding, an incompressible fluid dynamic (ICFD) solver, which is incorporated in the LS-DYNA (software which annualizes failure analysis of ships), is used. To adequately mesh this domain, initial elements were prescribed on the domain boundaries (Fig. 2a), and afterwards, the mesh algorithm extruded initial elements from the boundaries into the inner domain (Fig. 2b). The initial fluid mesh consisted of 1578 surface elements, which were then extruded, and raised to the number of 26630 elements. The free surface was modelled, and divided water and air.

Finite Element Modelling of damage and element deletion was not possible because of the software limitations. The ICFD cannot be combined with damage mechanics, so instead of modelling it, the point load is introduced as water weight. Load from flooding was coded using Fortran, and it incorporated Bernoulli's equation.

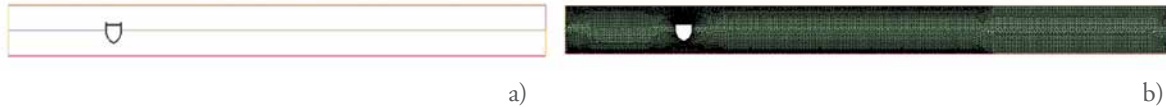


Fig. 2 Numerical domain: a) initial, b) extruded (author: Š. Sviličić)

$$\int_p \frac{1}{\rho g} dp + \frac{u^2}{2g} + z = const \tag{1}$$

$$u = \sqrt{2gz} \tag{2}$$

$$Q = \int_A u \cdot n dA, \tag{3}$$

where p is pressure, g represents gravity, u is the velocity field, z is fluid level height, Q is water flow, n is a unit vector, and A is the surface which in this study case represents the hole in the ship’s hull.

For this type of analysis, implicit dynamics was used, with a time step of 0.1 seconds. The total simulation time varied between 25 and 70 seconds. Implicit dynamics use the Newmark method, with time integration constants  $\beta=0.4$  and  $\gamma=0.6$ . To simulate rough weather conditions, the wave is generated at the boundary as a Stokes second-order wave, with a height of 0.8m and a length of 20 meters. Finite Element Modelling of the structure is simple, and consists of 500 finite shell elements.

### 2.3. Case studies

As every simulation runs for approximately 2 hours, many case studies are done, so the conclusion can be drawn, and a correlation between different parameters can be found. Case studies are varied based on the inner ship geometry, hole diameter, hole position as well as water velocity, e.g., calm water or waves. Table 1 presents all the cases with added descriptions.

Number	Description
1.	Bigger hole, Low position A1 → height=1.6m, d=0.2m
2.	Bigger hole, High position A2 → height=0.8m, d=0.2m
3.	Smaller hole, Low position A3 → height=1.6m, d=0.05m
4.	Smaller hole, High position A4 → height=0.8m, d=0.05m

Number	Description	Number	Description
1.	C1 – Calm water – Bigger hole – Lower position	10.	C3 – Waves – Smaller Hole – Lower position
2.	C1 – Waves – Bigger Hole – Lower position	11.	C3 – Calm Water – Smaller Hole – Higher position
3.	C1 – Calm Water – Bigger hole – Higher position	12.	C4 – Waves – Bigger Hole – Lower position
4.	C1 – Calm Water – Smaller Hole – Lower position	13.	C4 – Calm Water – Bigger Hole – Lower position
5.	C1 – Calm Water – Smaller Hole – Higher position	14.	C4 – Calm Water – Bigger Hole – Higher position
6.	C3 – Calm Water – Bigger Hole – Lower position	15.	C4 – Calm water – Smaller Hole – Lower position
7.	C3 – Waves – Bigger Hole – Lower position	16.	C4 – Waves – Smaller Hole – Higher position
8.	C3 – Calm Water – Bigger Hole – Higher position	17.	C4 – Calm water – Smaller Hole – Higher position
9.	C3 – Calm Water – Smaller Hole – Lower position		

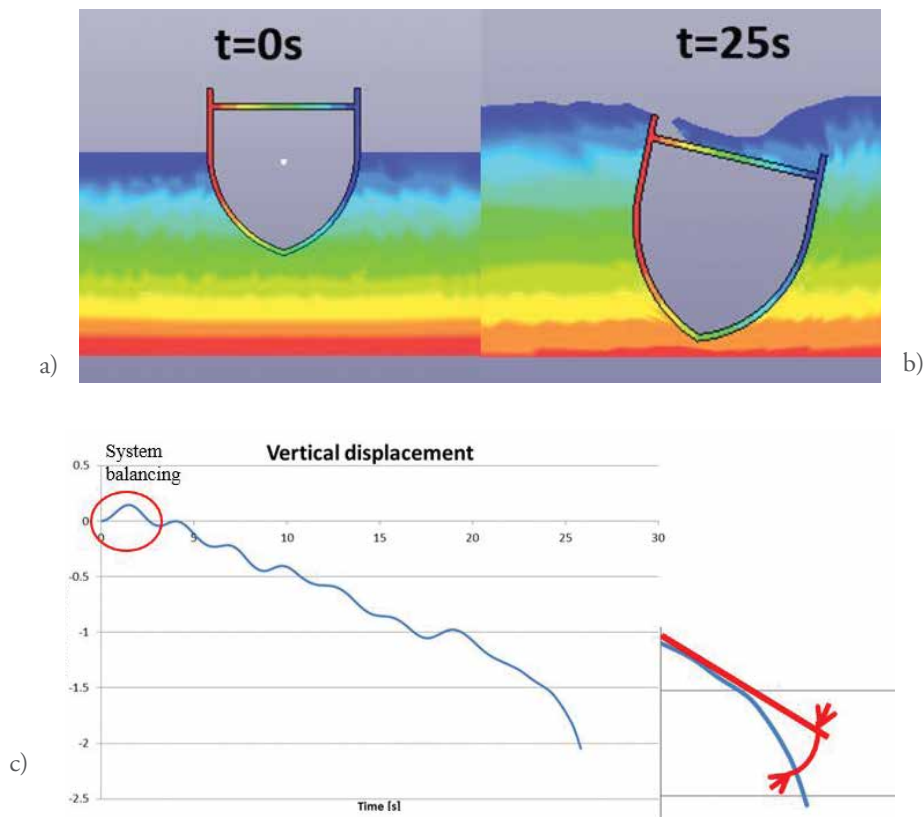
Tab. 1 All case studies

### 3. Results

#### 3.1. Ship with one compartment

For the ships with one compartment, the flooding scenario is straightforward. Water penetrates the internal chamber and causes slight disbalance of the ship, due to the surrounding fluid pressure, until the end when water reaches the deck. The first scenario, C1 with initial position of the ship (Fig. 3a) and final position of the ship (Fig. 3b) are shown. Flooding of the ship's interior is intense and due to the shape of the hole, the volume rate of leaking water is big. The initial three seconds do not include ship flooding, instead, they are used to let the system naturally stabilize in the neutral position. These three seconds are used for all the analyses.

The ship's centre of gravity is tracked over a period. The initial period (Fig. 3c, marked red) has slight oscillation due to the system balancing, after which the flooding is started. The period from the third until the 23<sup>rd</sup> second has slight oscillation, due to the surrounding oscillation of pressure. After 23 seconds, water fills in the deck and an abrupt change in the ship's centre of gravity is noticed. This means that the ship lost buoyancy, and its sinking is inevitable.



**Fig. 3** C1 ship case a) initial position; b) final position and c) vertical displacement of ship centre of gravity (author: Š. Sviličić)

#### 3.2. Ship with three compartments

As damage introduction is not feasible while using ICFD analysis, a predefined flooding scheme should be introduced for ships with more compartments. Two different flooding schemes are presented for ships with three compartments. All internal holes are of the same size, and the scheme is applicable for both, higher-positioned holes (0.8 m from the free surface, Fig. 4a) and lower-positioned holes (1.6 m from the free surface, Fig. 4b).

Next, the position of the centre of gravity of each compartment is compared for both cases, on calm water (Fig. 4c) and on waves (Fig. 4d). Due to the unbalanced mass caused by flooding, the rolling of the ship is much bigger than in the case of a ship with one compartment (Fig. 4c). The centre of gravity of each compartment shows a spike in displacement at five seconds due to rolling from water ingress on one side. Further ship oscillation with lower amplitude continues until water starts to enter the second compartment and pushes it down at approximately 23 seconds. In the case with waves (Fig. 4d), the influence of waves is visible. A high displacement peak occurs around the fifth second, due to the wave impacting the ship. Again, after 20 seconds, linear sinkage is visible after the water reaches the deck.

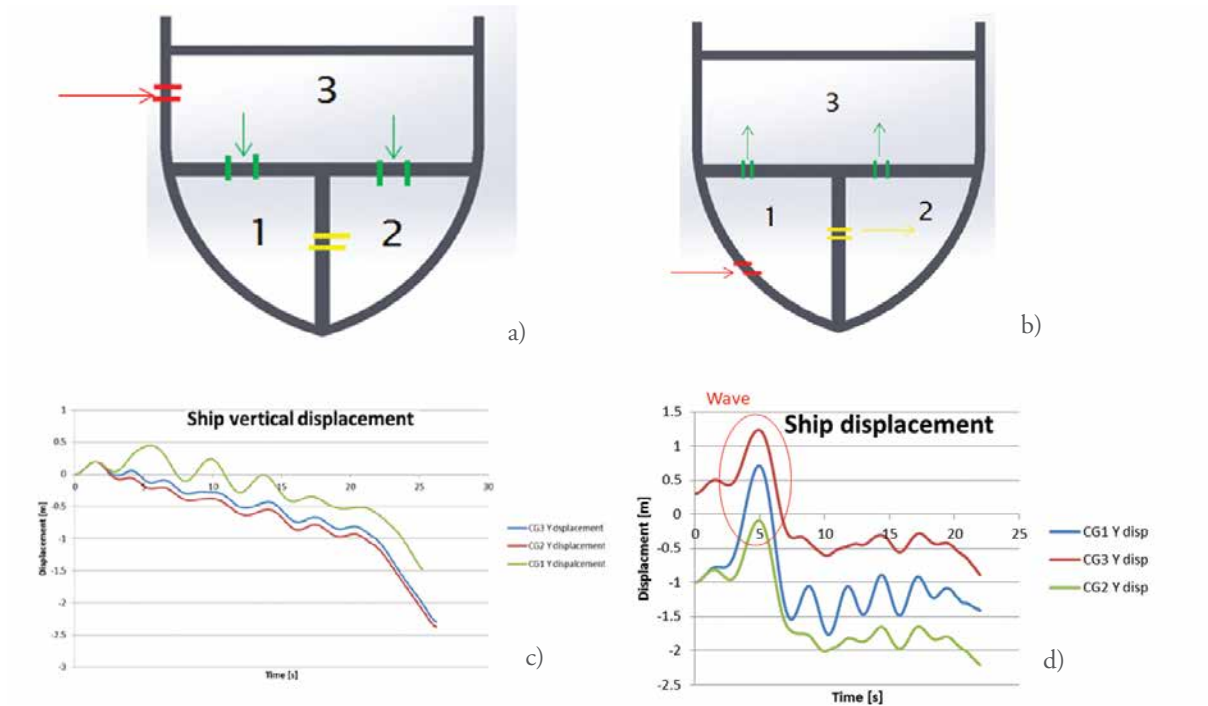


Fig. 4 C3 ship case with flooding scheme a) flooding starts at the top compartment; b) flooding starts at the bottom compartment; c) vertical displacement on calm water and d) vertical displacement on waves (author: Š. Sviličić)

### 3.3. Ship with four compartments

As position of the hole is defined for ship with three compartments in previous figures (Figs 4a and 4b), the same logic can be applied to the ship with four compartments, but further explanation of interior compartments flooding is needed. When water ingress starts at the upper hole (Fig. 4a), water passes through compartment 3 holes (Fig. 4a, marked green) and fills both compartments 1 and 2 simultaneously. After both compartments 1 and 2 are full, compartment 3 starts to fill up. If water ingress starts at the bottom hole, the flooding scheme is different (Fig. 5). Flooding initially starts at compartment 1 (CG1), which is filled until the interior hole (positioned at the middle of the height) is reached. Then, compartment 2 (CG2) is filled, while the force in compartment 1 is constant until the water level between the two compartments is equal. Finally, the water level in the two compartments continues to rise and fills the final, third and fourth compartments (CG3 and CG4).

As in the case of a ship with three compartments, a ship with four compartments has a defined flooding scheme. The results for Case 12 are shown (Fig. 6). Opposed to the ship with three compartments, ships with four compartments have a bigger roll due to constant mass disbalance during flooding (Fig. 6b). If the hole diameters are compared, less roll of the ship, and a bigger time till buoyancy loss is visible (Figs 6c and 6d), which shows that a small hole diameter prolongs buoyancy loss for more than 40% of the time making it the less severe case.

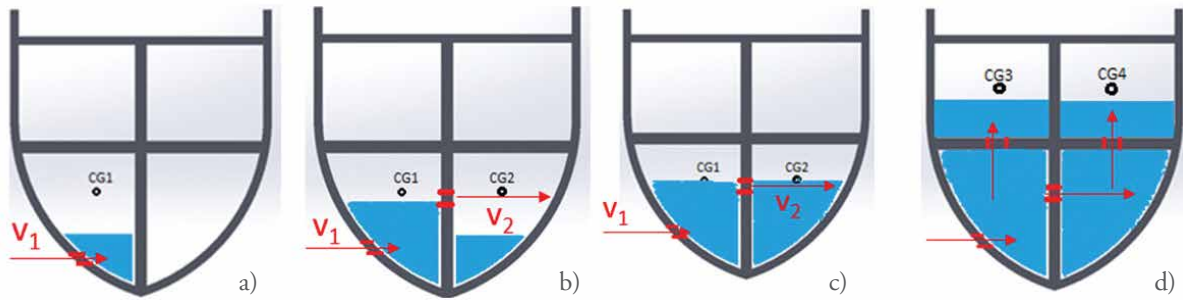


Fig. 5 Flooding algorithm for the lower hole (author: Š. Sviličić)

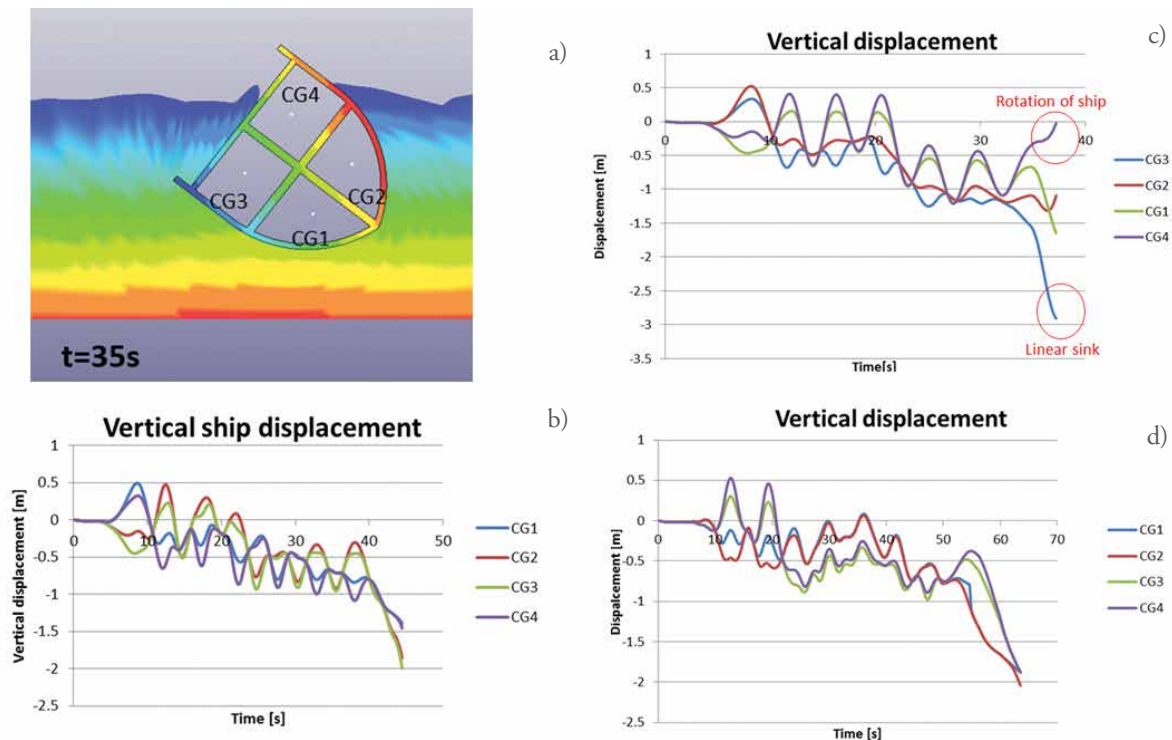


Fig. 6 C4 ship case: a) final position of Case 12; b) vertical displacement for Case 12; c) comparison of displacement for Case 13, and d) comparison of displacement for Case 15 (author: Š. Sviličić)

## 4. Conclusions

Results from all the case studies are shown in Table 2. It is shown that the size of the ship damage, i.e., hole diameter is a crucial parameter which has the biggest influence on the flooding time, more than the position of the hole. When assessing the different designs, the increased number of compartments caused bigger rolling of the ship, which led to more ship-on-deck effects, but a higher time till stability loss in general. The application of waves showed that for the same set-up (hole diameter, hole position and internal design), the time till loss of stability is slightly shorter, on average 10% less till the loss of stability. Additionally, as expected, waves generated more rolling of the ship, which caused more water on the deck, decreasing the time till buoyancy loss.

While the application of the 2D analysis approach for flooding simulation is a big simplification of such a complex case, it gives a quick solution for parameter study, and can potentially help in the assessment of how the given parameter influences flooding. Additionally, it helps in the assessment of the value of the parameter in real ship forensics, and gives good guidelines for some parameters such as hole position or diameter, which should be used in real 3D simulations.

C1 – one compartment	Time [s]	C3 – three compartments	Time [s]	C4 – four compartments	Time [s]
1.	25	6.	26	12.	35
2.	22	7.	25	13.	44
3.	32	8.	27	14.	43
4.	43	9.	56	15.	63
5.	46	10.	53	16.	57
		11.	59	17.	66

Tab. 2 Results from all the case studies

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