INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED15
27-30 JULY 2015, POLITECNICO DI MILANO, ITALY

ARCHAEONICS – HOW TO USE ARCHAEOLOGICAL SOLUTIONS FOR MODERN PRODUCT DEVELOPMENT.

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Abstract

This paper addresses the fact that product development often tends to "reinvent the wheel". By inventing the Archaeonics methodology / Archaeology-inspired-design (AID), we present a systematic approach to identify suitable archaeological solutions and make them useable for modern engineering issues. For this, we use problem abstractions and analogy search methods from TRIZ and biology-inspired design. The archaeology-inspired design approach was successfully evaluated in the context of a water cistern building project in Tanzania which is coordinated by the German chapter of "Engineers Without Borders".

Keywords: Archaeonics, Archaelogy-inspired design, Design methodology, Innovation, Sustainability

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Please cite this paper as:
Guertler, M. R.; Schaefer, S.; Lipps, J.; Stahl, S.; Lindemann, U.: *Archaeonics - How to use archaeological solutions for modern product development*. In: Proceedings of the 20th International Conference on Engineering Design (ICED15), Vol. 1: Design for Life, Milan, Italy, 27.-30.07.2015

1 INTRODUCTION

The goal of product development is the creation of products, which fulfil the needs of users. To achieve this, companies continuously develop new products and new technologies. Innovation research also focuses on new approaches fostering radical innovations. At the same time, there are frequently scientific and popular-scientific reports about discoveries of lost or old technologies, such as mud bricks as heat-insulating building materials, "*ferrum noricum*" as a form of ancient Roman high performance steel (Straube et al., 1996), or "*opus caementitium*" as a form of ancient Roman high performance concrete (Hoferichter, 2013). As already reports of ancient pneumatic engines of Heron of Alexandria showed, ancient technologies were quite elaborate (Greenwood and Woodcroft, 1851). These ancient technologies are often as good as modern technologies or even better. For instance, the analysed *opus caementitium* shows high compressive strength and the ability to bind radioactive material (Hoferichter, 2013) based on Lin et al. (2013). The reasons for their disappearance can be manifold from an only local occurrence to the down of an entire civilisation such as the west Roman or the Aztec empire.

Hence, due to the impressive capabilities of some old technologies, the question arises: is it necessary to frequently reinvent the wheel or is there a way to purposeful identify and use old technologies and solution concepts? Analogously to similar concepts such as biology-inspired design, we call the regarding approach "*archaeology-inspired design*" or based on Dotterweich et al. (2010) "*Archaeonics*". We consider its primary application in fields where technical solutions are required which are affordable, robust, easy to assemble and maintain, and not focussing on high-tech solutions, e.g. in the context of design for the developing world.

This paper presents an initial methodical approach for identifying and assessing potential archaeological solutions for a modern engineering issue. For this, we use problem abstractions and analogy search methods from TRIZ and biology-inspired design. The *archaeology-inspired design* approach was successfully evaluated in the context of a water cistern-building project in Tanzania, which is coordinated by the German chapter of "*Engineers Without Borders*" (www.ingenieure-ohne-grenzen.org). The gained insights can also be used for other analogy-based innovation methods such as cross-industry *Open Innovation* (Enkel and Gassmann, 2010). Due to simplification reasons, in the following we will use "technics" as a synonym for "technologies and solution concepts".

2 STATE OF THE ART: ANALOGY FORMATION

The basic idea of archaeology-inspired design is the transfer and adaption of existing ancient technics instead of a "reinvention of the wheel". The resulting research question is: "*How can modern engineering tasks be structured to allow the generation of new solution ideas by the utilisation of ancient technics?*" In the following, we give an overview about the limited literature of *Archaeonics* publications, followed by a short introduction to analogy formation approaches (e.g. TRIZ, Bionics).

2.1 Archaeology-inspired design

The existing literature about archaeology-inspired design is limited. For instance: Dotterweich et al. (2010) introduced the term "A*rchaeonic(s)*" which is a combination of "*archaeology*" and "*technics*". They defined it in the context of environmental management as a methodology "*to investigate past human-environment systems to develop sustainable long term successful strategies with high efficiency, resulting in a minimum of resource use and an expected high capacity of adaption to today's and future environmental management strategies and challenges*". In interdisciplinary workshops with archaeologists and civil engineers, topics from both fields were discussed. Analogously to a technology-push approach, the goal was the identification of promising ancient technologies (e.g. Roman, Aztec) and potential modern fields of application (land utilisation, sanitary systems).

Schön (2014) and Heinrichs (2014) also use workshops to foster an interdisciplinary exchange about a modern use of Roman and Carthaginian/Punic cistern technics with the focus on plaster.

Ferrand and Scarborough (2012) suggest using ancient Maya water storage systems as low-tech solutions for the modern inhabitants of the former Maya regions. By the use of old "aguadas", an impounding reservoir, rainwater can easily be collected and stored.

All existing publications have in common that they lack a methodical approach for the search and adaption of technics to modern engineering tasks. They usually use interdisciplinary workshops supporting (informal) exchange between archaeology and modern disciplines (Dotterweich et al., 2010, Heinrichs, 2014, Schön, 2014) or stay within specific geographical regions analysing which technics are used now and were used in the past (Ferrand and Scarborough, 2012). They also focus on a direct transfer of technics in the means of technology-push. A technology-pull approach starting from a modern technical issue and searching for archaeological solutions using analogy formation and a transfer on a higher abstraction level (technologies, solution concepts) does not exist so far.

2.2 Overview of analogy formation

Analogy formation is used in product development to overcome mental barriers by developing solutions for engineering tasks, such as being caught in fix or old thought patterns or fear of making mistakes (Lindemann, 2009). By bringing the engineering tasks to another level of abstraction, new solution mechanisms can be identified and a solution concept be developed which is then transferred back to the original level of abstraction. Figure 1 illustrates the regarding procedure for Archaeonics.
Due to space reasons, in the following only three established approaches of analogy formation are presented. However, besides them also other approaches exist, such as Cross-Industry innovations in the field of Open Innovation (Enkel and Gassmann, 2010).

2.2.1 Bionics - Biology-inspired design

Bionics addresses the systematic search and technical realisation of concepts, procedures, processes and development principles of biological systems (Nachtigall, 2010). A basic element of Bionics is analogy formation focussing on functional analogies such as the elongated structure of a grass stalk and a television tower. There are different alternative procedures for Bionics. Nachtigall (2010) suggests a three-step approach starting with (1) basic research to understand a biological phenomenon, (2) abstracting biological concepts and analogy formation, and (3) realisation within a technical system. To support the identification of suitable technical system for a biological concept, similarity matrices can be used (Küppers and Tributsch, 2009), (Jordan, 2010). Figure 3 shows the similarity matrix adapted for Archaeonics. It contains a stepwise test of similarity: only if one test step is successful the subsequent test step is conducted, otherwise an iteration of the procedure is necessary. Other approaches focus on a problem abstraction in terms of function, property and environment to search unstructured research articles on the web (Kaiser et al., 2014), based on (Shu, 2010), (Vandevenne et al., 2013).

2.2.2 TRIZ - The theory of inventive problem solving

A methodology adapted and partly used with in Bionics (Vincent and Mann, 2002), is TRIZ, which was developed by G. S. Altshuller. Based on an extensive analysis of more than 40,000 patents he formulated three laws for technical systems (Altshuller et al., 2002), (Orloff, 2006):

1. "The development of technical systems follows specific patterns."
2. "It is necessary to overcome contradictions during processes of inventing."
3. "A small amount of solution principles underlies a great amount of inventions."

TRIZ splits the innovation process into three phases (1) analysis of tasks, (2) solving of challenges and (3) selection of solution concepts. For each phase, different supporting methods are defined.
An important method within the phase "analysis of tasks" is the TRIZ function analysis (Muenzberg, 2014). Based on a functional model of a system containing its useful and harmful technical functions, engineering tasks and points for improvement can be identified. Besides the "classical" TRIZ function model we also use the *Graphically Enhanced Function (GEF) Analysis* by (Muenzberg, 2014) in our Archaeonics methodology. The regarding model allows a direct mapping of functions to components and supports the system's comprehension, as illustrated in Figure 2.

2.2.3 Morphological analysis

The morphologic analysis separates and structures a system into its elements, e.g. functions, parameters, components (Zwicky and Wilson, 1967), (Löhr, 2012). These elements are modelled in the first column of a morphological box, as illustrated in Figure 4. The following columns contain existing or potential solutions for each element - in our case, e.g. solution concepts for fulfilling the function "clean cistern". The approach is solution-neutral by openly collecting solutions and supports the understanding of complex systems. The part solutions of each row are then combined to one or different alternative total solution concepts.

3 RESEARCH METHODOLOGY

Based on a literature review of *Archaeonics*, three key goals of the *Archaeological-inspired-Design (AID)* methodology were identified: (1) a technology-pull approach, (2) solution search on an abstract level, and (3) the development of a systematic approach. In the following, established approaches in the field of analogy formation were identified, contained elements were analysed and combined to a consistent methodology. For this, the 'classical' procedure of analogy formation (Lindemann, 2009) was enhanced by a requirement analysis (Pahl et al., 2005), TRIZ-function analysis (Altshuller et al., 2002), GEF analysis (Muenzberg, 2014), similarity matrix (Küppers and Tributsch, 2009), morphologic boxes (Zwicky and Wilson, 1967) and use-value-analysis (Zangemeister, 1976).
For the initial evaluation, we selected a low-tech example. Though we assume AID might also be used for high-tech development systems, we see its primary field of application in low-tech systems focussing on an easy assembling, robust design and easy maintenance. Thus, we chose a water cistern-building project in Tanzania coordinated by the German chapter of *Engineers Without Borders*.

4 ARCHAEONICS - ARCHAELOGY-INSPIRED DESIGN (AID)

In the following an overview of the *Archaeology-inspired-Design (AID)* methodology is given. Subsequently the single steps of the methodology are explained in more detail using the data from the cistern project in Tanzania. In contrary to existing *Archaeonics'* approaches (cf. chapter 2), this paper presents a new methodology using a systematic top-down approach starting with a technical problem/issue and identifying potential archaeological solutions. The solution search and transfer is conducted on an abstract level of solution concepts and ideas such as technologies or building principles. A direct application of archaeological components is not focussed. Since Dotterweich et al. (2010) state the relevance of humans as potential risks for a successful application, we also consider cultural systems by analysing context factors within the similarity matrix. As illustrated in Figure 1, the AID methodology consists of six steps and is based on the process of analogy formation (Lindemann, 2009).

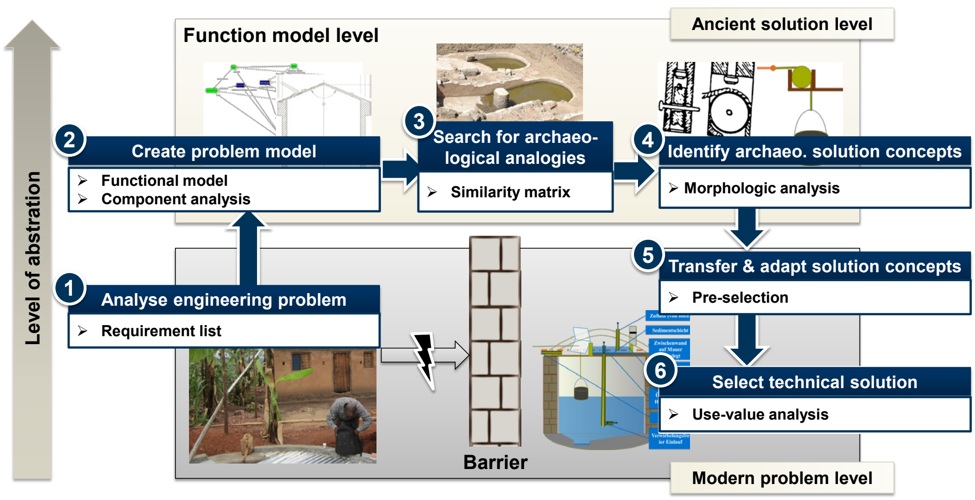

Figure 1. Methodology of archaeology-inspired design / Archaeonics

1. **Analyse modern engineering problem**
   In the first step the system of interest, its boundary conditions and the engineering task/s are analysed and solution-neutrally documented in a requirement list.
2. **Create problem model**
   This step contains a component and function analysis of the system of interest. The results of this step are e.g. a TRIZ function model and a component-function/*GEF* model. In the following, those are used to set up the morphologic box.

3. **Search for archaeological analogies**
   Based on the system analysis in step 1, step 3 identifies relevant archaeological search areas/cultures. The search is supported by the use of a similarity matrix.
4. **Identify archaeological solution concepts**
   Within the identified archaeological area, potential solution concepts are identified. The use of the morphologic box supports the search for partial solutions and a structured documentation.
5. **Transfer and adapt solution concepts**
   In order to develop alternative technical solutions, the identified partial solution concepts are assessed, prioritised, adapted, and transferred to the system of interest. By combining different partial solutions, alternative entire solutions can be derived.
6. **Select technical solution**
   By a use-value-analysis, the characteristics of each alternative solution are analysed and the solutions prioritised. This serves a basis for the selection of a technical solution, which is further developed in the following.

4.1 Step 1: Analyse modern engineering problem

The first step analyses the modern system of interest to allow a holistic understanding of the system and derive a requirement list. This serves as basis for the following development of a technical solution. The requirement analysis contains requirements from different sources such as users, product developers, building teams as well as legal regulations. An important source for cistern requirements were expert interviews with members of *Engineers without Borders*. To support the analysis, checklists with different requirement categories can be used (Pahl et al., 2005).
In general, a cistern is a covered reservoir for storing rain water (Hodge, 2002) which includes current rain water reservoirs in Tanzania as well as Roman or Punic ones. To improve the water supply in Tanzania, a local NGO "*MAVUNO*" and the German chapter of *Engineers without Borders* started a cistern building campaign in 1995. Over 300 cisterns have been built so far. The regarding geographical, cultural and economic boundary condition of the cistern project were also analysed and documented within the requirement list.

4.2 Step 2: Create problem model

The goal of the second step is the abstraction of the modern technical problem by developing a component and function model. The models support the subsequent search for analogies. An important factor is the choice of the right level of detail in order to allow a fruitful analogy search but also to keep the task manageable (Muenzberg, 2014).
The component analysis and modelling consists of three steps, cf. (Klein, 2007), (Muenzberg, 2014):
(1) Firstly, the relevant components of the system and the super-system (the system's environment) are identified. (2) Then the interactions (e.g. spatial) between them are analysed by the use of a *Design Structure Matrix* (DSM) (Maurer, 2007). (3) Based on the component interrelationship analysed in (2), the components' functions are analysed.

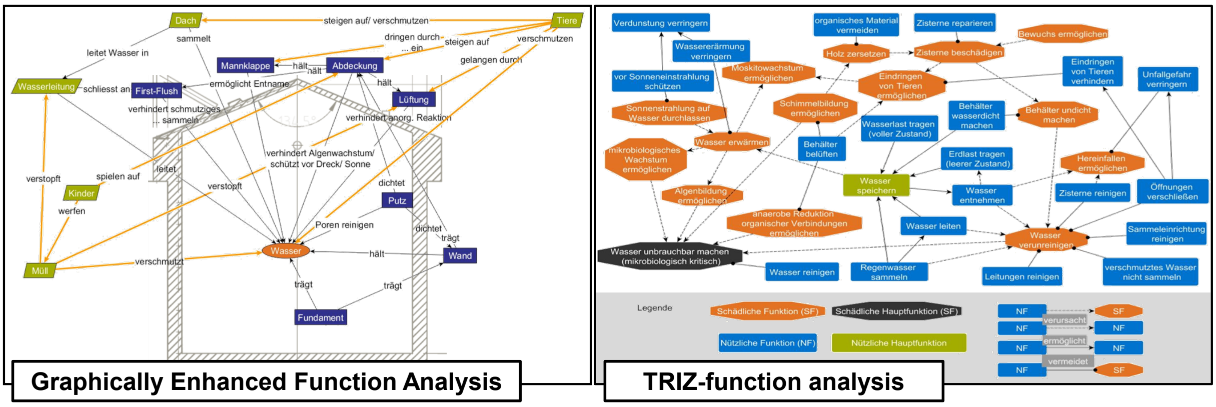

Figure 2. Graphically Enhanced Function and TRIZ-function Analysis of Tanzanian cistern

This function analysis itself uses two approaches: (1) a top-down approach starting with the systems main function and detailing it into sub-functions; and (2) a bottom-up approach starting with the

components' functions and clustering them to superordinate functions (Lindemann, 2009). Besides useful function also harmful functions are identified as well as their interrelations (Terninko et al., 1998). To support the identification of functions and interrelations, TRIZ-function analysis is used (as depicted in Figure 2) as well as DSM which allows the derivation of function clusters. By the use of a Domain Mapping Matrix (DMM) the dependencies between components and functions can be analysed (Maurer, 2007). An additional method is the *Graphically Enhanced Function Analysis* (Muenzberg, 2014), as illustrated in Figure 2. It supports the system's understanding of the developer by providing a direct graphical mapping of components and regarding functions.
Within the function analysis, harmful function are of special interest, which are not or only insufficiently covered by preventive useful functions. Those functions and relevant but deficient useful functions represent potential points of improvement and the subsequent analogy search.
Relevant functions in the context of the cistern project were for instance: "reduce water warming", "clean cistern", "clean water", "protect against sunlight insolation". For the following methodology steps, all functions are documented in the left column of a morphologic box, as shown in Figure 4.

4.3 Step 3: Search for archaeological analogies

Based on step 1, step 3 defines archaeological search criteria. In the cistern project, these were expertise with water buildings and technics, similar living conditions (e.g. water shortage) and the same geographical region. The last criterion was a special limit to keep the initial evaluation of our approach manageable. For future application, this criterion should be neglected to open up a broader solution space.

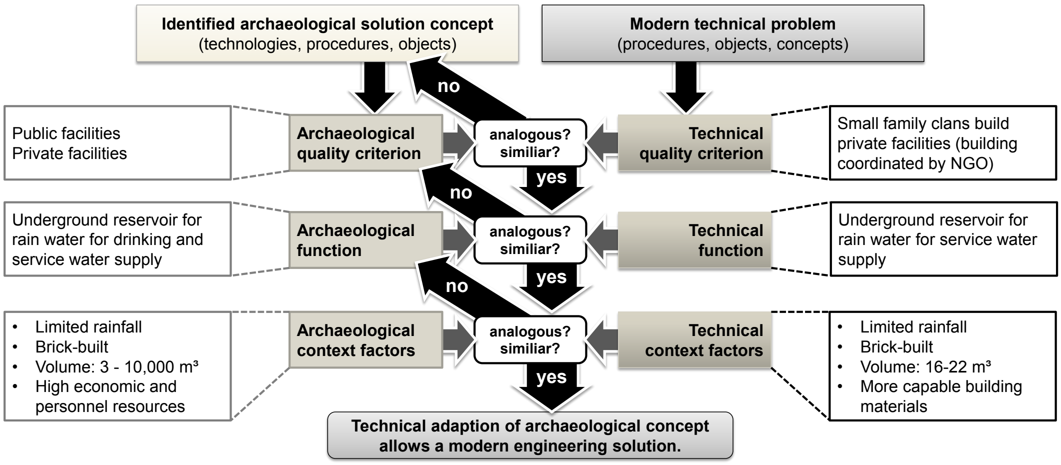

Figure 3. Archaeonics' similarity matrix (adapted from (Küppers and Tributsch, 2009))

Subsequently different ancient cultures were identified by an internet search using the search term "ancient high culture" and interviews with archaeologists of the department for Classical Archaeology at the Ludwig-Maximilians-University in Munich. Promising ancient cultures were e.g. Romans, Carthaginians, ancient Greeks, ancient Chinese, Maya, Aztecs or Incas.
Based on the defined search criteria these potential relevant ancient cultures were assessed, and the focus set on Romans and Carthaginians due to the same geographical location. To validate the selected cultured, we used the Archaeonics' similarity matrix, depicted in Figure 3. The technical criteria (quality, function, context factors) are/were derived from step 1, while the archaeological criteria were assessed by interviews with experts from the Classical Archaeology. The results show that the search area of Roman and Carthaginian/Punic built cisterns is suitable.

4.4 Step 4: Identify archaeological solution concepts

After selecting the archaeological search areas, step 4 searches for potential (partial) archaeological solutions within these areas. Based on Kalogerakis (2010), there are different search options. Of them, we used a media-based and a persona-based search. The media-based search included a keyword-search in German, English and French (Italian and Spanish are planned for the future) in digital databases: "Zenon DAI", the university library database system "OPAC" and the database "Baufachinformation" of the Fraunhofer IRB (civil engineering) as well as paper-based sources such as publications of water-historical research (Mitteilungen aus dem Leichtweiss Institut für Wasserhistorische Forschungen), the "architecture" and "Romans in North Africa" section of the archaeological library. The persona-based search included expert interviews with archaeologists from Ludwig-Maximilians-University in Munich and Eberhard-Karls-University in Tübingen.

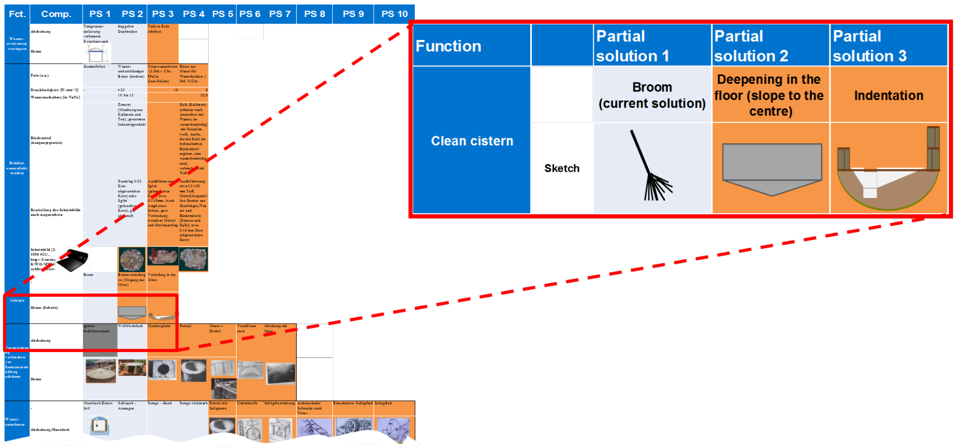

Figure 4. Section of morphologic box (light shade: modern - dark: archaeological solutions)

The goal was gaining a broad field of possible partial solutions in the context of private cisterns. Relevant sources were for instance (Brinker, 1990), (Lamprecht, 1996), (Schön, 2014), (Wilson, 1998), (Wölfel, 1997), etc. To evaluate the 'newness' of the archaeological solutions, we also recommend searching for alternative modern solutions. In total, we found 27 archaeological solutions and 15 modern ones. Five archaeological partial solutions regarding cisterns' roofs were excluded since the roof was defined a constraint and set as a concrete pointed roof. By the use of small sketches or pictograms, the comprehensibility of the single partial solutions can be increased. Figure 4 depicts an overview of the filled morphologic box as well as three partial solutions for the function "*clean cistern*" in more detail. While the current modern solution uses a broom, archaeological solutions also contain a centric deepening in the cistern's floor or a specifically shaped indentation (Brinker, 1990).

4.5 Step 5: Transfer and adapt solution concepts

After collecting potential partial solutions, in step 5 all partial solutions are analysed regarding their potential for deriving a technical solutions. The assessment is based on expert discussions with archaeologists and engineers. KO-criteria derived from the requirement list of step 1 support the assessment process by focussing the effort of a detailed analysis on the promising partial solutions. As the level of abstraction of archaeological solutions can differ, also the assessment effort differs.
Based on the promising partial solutions, different alternative total solutions are derived. The resulting total solutions can range from mainly modern ones with only one archaeological partial solution to mainly archaeological solutions. It is important to consider that a higher degree of archaeological solutions causes more changes in the existing system, which might negatively affect the cost-benefit analysis in step 6. Besides, not all partial solutions are compatible with each other. Subsequently, the alternative solutions are transferred to the modern problem level, as illustrated in Figure 1.

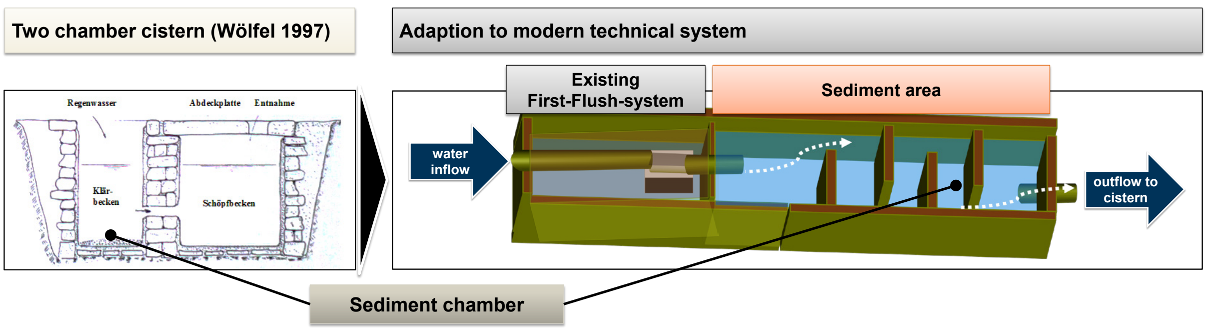

Figure 5. Transfer of a two-chamber cistern setup to the modern system

As Figure 5 shows, the archaeological solution cannot directly be transferred but needs to be adapted to the specific modern technical system. It needs to be evaluated if modern technics and materials can foster archaeological solutions. In the example depicted in Figure 5, the effect of the sediment chamber (Wölfel, 1997) can be increased by a preceding *first-flush-system* which removes bigger impurities such as leafs that gather on the roof after a dry-period. The sediment chamber allows to clean finer impurities as a second cleaning step. This is additionally supported by the maze structure of the water channel. Analogously the partial solutions for the other seven system-functions of step 2 were transferred.

4.6 Step 6: Select technical solution

Step 6 contains a value-benefit-analysis of the alternative solution combinations and the existing system. Though the new combination of partial solutions allows architectural innovation (Hauschildt and Salomo, 2007), the corresponding effort and costs for changing the system might exceed the expected benefits. The assessment criteria for the value-benefit-analysis are derived from the requirement list of step 1 and weighted by experts responsible for the modern system (here members of *Engineers without Borders*). The results of the analysis themselves are evaluated by a sensitivity analysis and plausibility analysis, according to (Lindemann, 2009).

Criterion	Criterion weight	Part. Goals	Part. weight	Absolute weigh
Water Quality	0,3	Reduce coliformes	2,7	0,80
		Reduce enterokokks	2,7	
		Reduce total number of aerobe bacteria	2,7	
		Reduce water temperature (lower 24° C)	2,0	
Technical Functions	0,2	Easy reachable surfaces	1,00	
		Allow complete evacuation	3	
		Use corrosion-resistant materials	2	
		Reduce warming	3	
		Increase water volume	1	
Ergonomics & Safety	0,1	Allows easy cleaning	3,00	
		Allow easy extraction of water	6,00	
		Prevent falling in of humans and objects	1,00	
Building process	0,2	Allow easy building and assembling	2,00	
		Time expenses for building	3,00	
		Applicability for Tanzania	5,00	
Economy	0,2	Building costs (material and labor)	9	
		Reparation costs	1	
Sum	1,00		50,00	

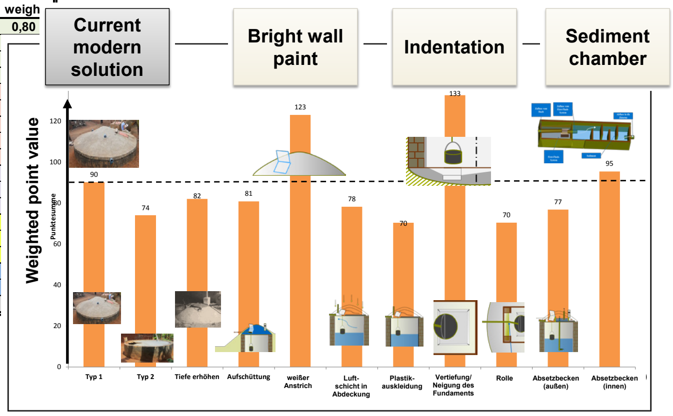

Figure 6. Assessing criteria and results of value-benefit-analysis

In the evaluation case of the cistern project, we derived five criteria categories containing two to five criteria: Water Quality, Technical Functions, Ergonomics & Safety, Building process and Economy.
By weighting first the categories and then the single criteria, the involved experts are forced to reflect and compare the importance of the superordinate project goals. Figure 6 depicts the weighted categories and criteria.
The assessment of the criteria is based on expert interviews and using a geometrical point scale: *1 (insufficient), 3 (ok), 9 (good) and 27 (very good)*. Figure 6 shows the weighted sum of all criteria for different solution combinations after an evaluating plausibility and sensitivity analysis. The current solution is depicted on the left side. Three partly archaeological solutions show potential benefits compared to the current solution:

- By the use of bright (white) wall paint, the sunlight insolation and a resulting warming of the cistern's water can be reduced. It positively affects the water quality. The investment costs are low.
- Though the additional costs for an indentation in the cistern's floor are higher, it increases the water quality by collecting dirt and simplifies the cleaning of the cistern.
- An additional sediment chamber can support the cleaning function of the existing *first-flush-system* and reduce the dirt import into the cistern. However, the sediment chamber represents an additional area, which needs to be cleaned by the users to obtain its positive effect.

5 DISCUSSION

This paper presents an initial approach to systematically identify and adapt archaeological solutions to solve modern engineering problems/issues. According the subjective assessment of experts

from *Engineers Without Borders,* the derived solutions bear the potential of significant improvements towards the current solution. Especially the three previously presented solutions will be considered for future modifications of the cistern since they provide benefit to the cisterns currently used.
However, despite the positive results from the evaluation there are still some points of improvement, which needs to be addressed in the following enhancement of the AID methodology. Besides the missing support selecting a suitable degree of abstraction in step 2, especially the identification of search areas in step 3 is a crucial point - comparable to cross-industry innovation (Enkel and Gassmann, 2010). So far, this identification is based on the experience of the involved experts. When looking for archaeological partial solutions in step 4, a big challenge is the quality and accessibility of the archaeological sources: on the one hand, the level of detail can vary from a rough textual description to detailed sketches of specific excavations. On the other hand, often the publications of important archaeological findings are delayed due to financial issues or missing work force to process and publish the findings. For instance, Schön (2014) presents results from a workshop/conference conducted in 2011. This also makes the involvement of such experts necessary. In the context of an increasing electronic publication process (instead of paper-based monographs), the access to archaeological literature will improve. This allows the adaption of search approaches such as from Bionics (Kaiser et al., 2014) and (Vandevenne et al., 2013). Thus, the state of the art is fragmented. In addition, the type of publication differs from engineering publications, which requires different search strategies.
The presented cistern example presents a low-tech issue since we aimed at a case study with context factors similar to the ancient cultures. Instead of high-tech solutions, people in Tanzania require cheap, robust and easily constructible and repairable solutions. This is valid for an initial evaluation but the future it also needs to be evaluated if and how the AID-methodology can be applied for high-tech issues.
The methods and findings gained within the AID-methodology might also support other analogy formation approaches.

6 CONCLUSION AND OUTLOOK

This paper addresses the fact that product development often tends to "reinvent the wheel". By inventing the Archaeology-inspired-design (AID) methodology (or "*Archaeonics*" (Dotterweich et al., 2010)) we present a systematic approach to identify suitable archaeological solutions which got lost over the centuries due to several reasons, e.g. the doom of civilisations such as the Aztec empire. The approach aims at making them useable for modern engineering issues. This includes the transformation and adaption of the archaeological solutions as well as a value-benefit-analysis.
In the presented case study of the cistern project in Tanzania, the identified archaeological solutions provide robust and affordable cistern designs suitable for the modern context factors in Tanzania. They demand low requirements for the training of local workers, building technics and the availability of materials. In contrary, modern high-tech solutions are often not suitable for developing countries, such as downpipe-filtering systems or UV-lamp disinfection. These are costly, often not available and knowhow for an autonomous installation, usage and maintenance is missing.
Based on the identified points of improvement, we will further develop the AID methodology. In the context of follow-up work of the cistern project, the search focus is broadened to include additional cultures such as ancient Greek, ancient China, ancient Egypt, Mayas, Aztecs, etc. The issue focus can also be broadened to areas besides agriculture and water engineering. Since Archaeonics is a new analogy formation approach, we need to further explore its field of application as well as its direction, i.e. technology-push or pull. The experience with and parts of the AID methodology might provide valuable enhancements for other analogy formation approaches, e.g. search methods of step 3 could be adapted for cross-industry innovation.

ACKNOWLEDGEMENTS

The authors wish to thank Frerich Schön of the Eberhard-Karls-University in Tübingen for his valuable input and feedback to archaeological water buildings.

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