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Axiomatic design process in developing a model prototype rainwater harvesting infrastructure

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Abstract

This abstract presentation shall address issues arising from scarcity of water supply due to climate change, increasing demand of the urban population, limited water resource, and the inaccessibility to deliver water supply to rural communities of Papua New Guinea. The rainwater harvesting system is being considered. This paper shows the application of Axiomatic Design (AD) in designing of a prototype rainwater harvester for visual presentation of the infrastructure. The use of AD helps build the model without compromising its feature of the geographical set up of the place. It is gravity driven considering the rainfall scenario, the location, the demand, and health considerations.

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*Keywords:*Model prototype, rainwater harvesting, axiomatic design process

1. Introduction

Water supply scarcity is a pressing issue that demands an immediate solution as population increases geometrically worldwide. It is one of the biggest problems being faced by many societies and the whole world in the 21st century [1]. The overall earth's fresh water supply amounts only to 0.62 percent. The amount of available fresh water found in lakes, rivers, and groundwater supplies are decreasing due to the phenomenon brought by climate change [2]. The UNDESA study [1] reported that water scarcity attributes to the following conditions: inadequate natural resources (physical water scarcity or natural phenomenon) and poor management of the sufficient available water resources (economic water scarcity or human-made) as shown in the Fig. 1.

Nomenclature

AD	axiomatic design
CN	customer needs
DP	design parameter
FR	functional requirement
PV	process variable
PNG	Papua New Guinea
RHI	rainwater harvesting system

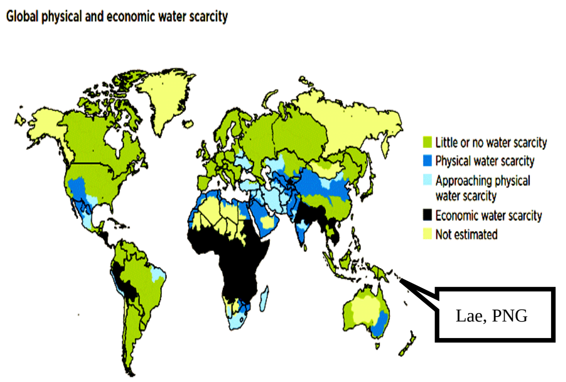

Fig. 1. A 2006 physical and economic water scarcity by country [1].

As shown in Fig.1, the PNG condition of water scarcity as of 2006 is "little or no water scarcity". The report of Guardian.com in 2009 said that about forty-five percent (40% - 45%) of 6.7 million population have sustainable access to improved drinking water and improve sanitation [3]. The

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2015 population estimated to be 7.6 million is continually increasing and will be needing more access to water. The goal of PNG government is to provide its people a 70% access to water by the year 2030 and 100% access by the year 2050, were critiqued by World Bank not on track to meet either the millennium goal or its national development targets [4]. The 1900 – 2012 records of the World Bank on PNG's monthly average precipitation were used to calculate the average rainfall every thirty years because a thirty-year period is an ideal measurement to assess climate patterns studied over a long time [5], as shown below.

Table 1. Average monthly rainfall for Papua New Guinea

Year (30 years)	Rainfall (mm)
1900 – 1930	261.68
1930 – 1960	258.94
1960 – 1990	260.53
1990 – 2012	260.34

The available rainwater in PNG has an average of 250.93 mm in more than century as shown in Fig. 2, which contributed to the available water supply that supports PNG's Millennium Development Goals (MDG) targets to have access both the sustainable water and sanitation about 70% by 2030 and 100% by 2050. The current strategies on access to sustainable water and sanitation cannot keep pace with rapid population growth. Water scarcity needs to be addressed so as to meet the MDG targets. Unless there is a significant and urgent investment in sustainable water supply and sanitation, the country is also unlikely to achieve its national goals to 2030. An account for the proper management of rainwater resource for sustainability is proposed in this paper to mitigate the impact of climate change. A role played by rainwater harvesting.

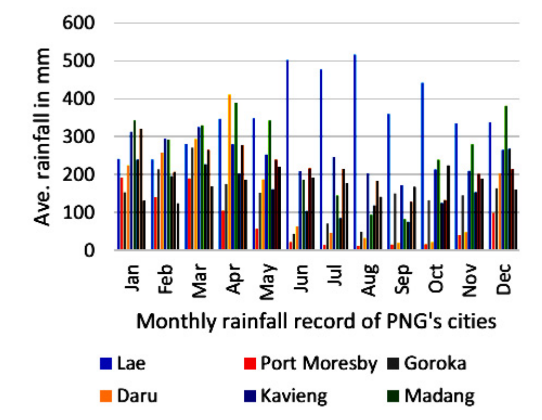

Fig. 2. An average rainfall (mm) of cities in Papua New Guinea

Rainwater is a gift from above [6]. For Papua New Guineans rainwater is their source for drinking water and other cleaning purposes. Many of the low-income population don't even have access to PNG water services except thru rainwater. The main reason why the government services such as water supply do not reach to the settlers is due to the "clannish culture" where most of the land in the country are customary land or owned by the clan. Many property owners hinder the development of access to government services that passes their property. Only very few afford to buy a water pump to get groundwater to supply the need. Since Lae City has a rainfall that ranges from 4000- 5800 annually, a rooftop rainwater harvesting has been employed by some household[7]. However, a communal rainwater harvesting infrastructure such as this was proposed. The prototype rainwater could provide a sustainable supply as compared to the individual rainwater harvesting through a roof that some households are used to. Improvised containers are being used and are susceptible to water contamination as shown in Fig. 3.

Fig. 3. (a)Rusted open container to collect rainwater. ; (b) open scrap freezer as container to hold rain water from gutter

The prototype of an RHI with a catchment has an area of 3,997.1 m2 as shown in Fig. 4 with dimensions of 88.6 m x 45.1m. It is estimated to have a building cost for one (1) unit of $220,000.00 (0.6 M in Kina, Papua New Guinea's currency, $1 = K3) or about $50/m^2 (K150/m^2). The estimated household population to be served by the prototype is 5,415 (the details of the calculation can be found in item 3.0 RHI designing the model of this paper). The infrastructure storage tank can hold about 11,320,500 liters (11.3 M m^3) annually or about 943,375 liters/day (943.4m^3/day). It provides an approximate annual investment of K0.05/liter (K0.15/m^3). The current price for one liter bottled water is K3.5 ($1.16) if this amount is used to calculate for such investment will cost a total of $425,600 (K 1,276,800.00), a savings of about 47%. One of the authors pays $2/gal (K6/gal) or K1.5/liter for a purified drinking water from a vendor.

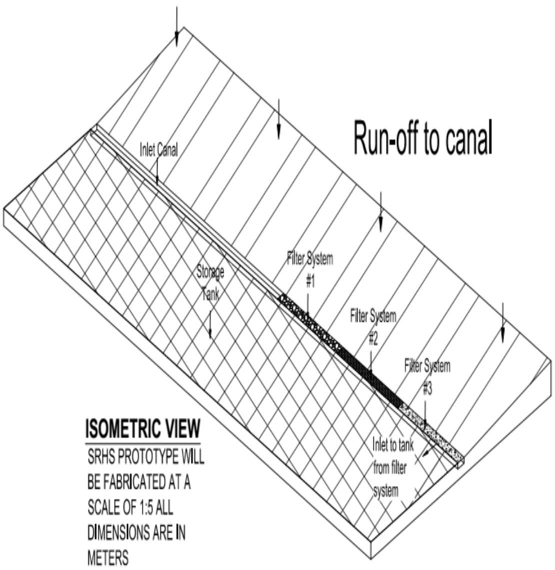

Fig. 4. The schematic diagram of the proposed prototype Sustainable Rainwater Harvesting System (SRSH)or system diagram of RHI

The authors are seeking investors to build the prototype rainwater and that our experience paves the way for us to sourcing and seeks funds from benevolent stakeholders or a grant from the government to finance this project. The result of our funding drive produces a grant from the Research Committee of the University amounting to $1,666.00 (K5000.00). The said grant can only build a model prototype (in smaller scale) with a ratio of 1:50. It shows the parameters of the infrastructure and simulates the rainwater harvesting mechanism. This model prototype was the exact and initial representation of an RHI design as to the dimension and the functionality of the system. The modeling and simulation of rainwater harvesting system were analyzed using the AD process.

2. The AD Process in modeling & simulation

The major components of rainwater harvesting system are rain and catchment area. To create a model prototype of an RHI that will represent the system must consist of the following: rain (simulation), catchment, filtration tank, storage tank, utility area (chlorination), and distribution tank. The catchment area will serve as a platform to capture rainwater on different scenarios (dry year, and wet year that portrays the behavior of rainfall pattern). Since rainfall pattern may vary, it must be designed that when the rain comes, it is critical to capture as much rainwater as possible. The model prototype will simulate or imitate the operation of a real-world process or system over time similar to what a prototype does, see Fig. 5. The image shows a rainwater harvesting infrastructure in Elisabeth, Jamaica (one of the author's home country). This method of harvesting rainwater is through a communal infrastructure that can cater to the growing population of the city.

Fig.5. (a) An elevated rainwater concrete catchment of Elisabeth, Jamaica; (b) the surface runoff and the storage tank of Elisabeth, Jamaica RHI

The complexity of the modeling and simulation is simplified using AD. Suh [8], the author of axiomatic design, states, "The goal of the axiomatic design is to establish a clear design basis that will improve technical design process based on logical and rational thought processes and tools." He further says that "One reason so many design mistakes happen today is that design is being done empirically on a trial-and-error basis." The AD concept will help the designers what they want to achieve. In our case, we wanted to make a model of an Rainwater Harvesting Infrastructure or RHI. After the building of a model, it must accurately simulate the rainwater harvesting system. The process AD process to include the AD mapping is shown in Fig. 6a and the AD decomposition as shown in Fig. 6b.

The AD intends to fast track, make better, and helps to communicate the design intent to come up with a best and cheaper design solutions to the intended system, RHI model-prototype. It also provides metrics for the progress and quality of the system. The AD mapping is a process to check if the intention is carried out as planned. The AD decomposition is a process to maintain the independence of the first axiom, the FRs. The DP's are the variables in the physical domain characterizing the design that satisfies the FRs.

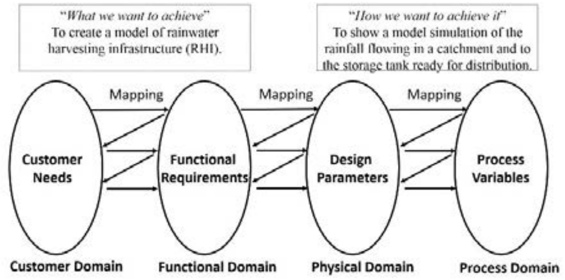

Fig.6a. AD mapping from CN to FR, to PD and to PV. Adapted from [7].

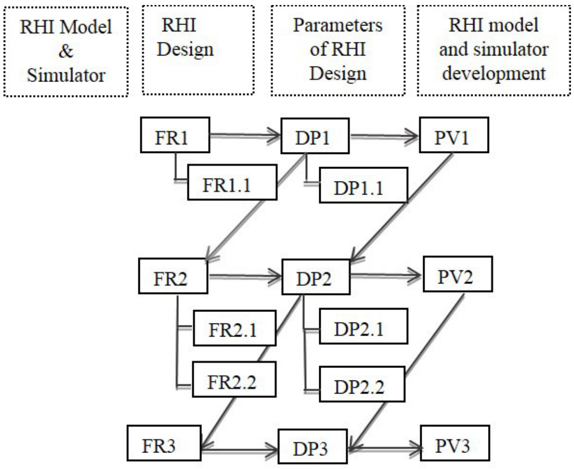

Figure 6b. AD decomposition of FR, of PD and PV. Adapted from [7].

The modeling aims to provide the functionality of the RHI prototype and see that the design simulates the actual physical parameters such as rainfall, the catchment, the filtering process the storage tanks and the outlet for distribution. The model prototype will reduce the trial and error in building the infrastructure. In a prototype, room for error can be fixed at a certain level with higher cost, and to rectify flaws in the design of a model prototype is cost wise. It serves as an experimental work in a laboratory scale that will showcase the most important feature (simulating rainfall scenario and collection process) in water harvesting. The rainwater harvesting infrastructure (model prototype) will help anyone get a good visualization of how the rainwater harvesting system design works. The display aim is to show investors, project developers, and any other interested party gets for their investment.

2.1 FR & DP Analysis

Table 2 shows the RHI model prototype design matrix. The design matrix shows a clear decision where many alternatives and varying criteria are of importance for consideration. Design matrices represent the analysis and the relationship of the FR's, the DP's domain. These matrices should eliminate complexity, which is maintaining the independence of the FR's, 1st Axiom. The FRs are written in the action word or verb [9], example; FR0 is to fabricate an RHI model prototype. Fabrication will require action to produce an RHI system. Therefore, the DPs should be in a noun form, and DP0 is the RHI system.

3. RHI Designing the Model Prototype

3.1 Factors Affecting the Model Prototype

In the creation of a model prototype, there are factors that designers of RHI considers. In the modeling of rainwater harvesting system have requirements such as first is to calculate the amount of rainwater for collection by that system, a function of the catchment area and the nature of collecting surface. Second, the nature of collecting surface relates to the material used in the model and other factors such as the slope of the catchment, sizing of the catchment area, the storage tank and the water tightness of the reservoir. The material selection has to comply with the design criteria that it is less in weight for convenience in carrying while in the development of the model. The material should also be transparent to be able to observe the behavior of the rain flow. Durability is another to be considered in the choice of the material to resist the water pressure. The amount of rainwater harvested is calculated by the formula [10]:

$$V = RAe \quad (1)$$

Table 2. RHI model prototype design matrix

	DPs	*RHI System*	*Weight less & transparent*	*coefficient of runoff, e*	*dimension of catchment*	*shower or rain*	*filter membrane*	*tank*	*chlorination*	*outlet*
	FRs	DP0	DP1	DP1.1	DP2	DP2.1	DP3	DP4	DP5	DP6
FRO	Fabricate an RHI model prototype	**x**	0	0	0	0	0	0	0	0
FR1	Determine the material to be used		**x**	0	0	0	0	0	0	0
FR1.1	Determine reliability of collecting surface		0	**x**	0	0	0	0	0	0
FR2	Estimate rainwater to be harvested		0	0	**x**	0	0	0	0	0
FR2.1	Simulate rain (dry & wet)		0	0	0	**x**	0	0	0	0
FR3	Remove dirt and other contaminants		0	0	0	0	**x**	0	0	0
FR4	Contain water		0	0	0	0	0	**x**	0	0
FR5	Protect water quality		0	0	0	0	0	0	**x**	0
FR6	Provide point for distribution		0	0	0	0	0	0	0	**x**

Where:
V is the Volume of runoff (liters/time)
R is the precipitation or rainfall (mm/time)
A is the footprint of the collection surface or area (m^2)
e is the efficiency of the collection surface

The formula shows that the catchment area is a function of the amount of runoff created by the rainfall as an amount of water harvested from the system. A flow coefficient influences a runoff. The prototype catchment made of concrete has coefficients of 0.7 – 0.8 while a model prototype used a transparent thermoplastic material value of 0.6 – 0.9 as shown in Table 3. It is an acrylic glass made of Polymethyl methacrylate (PMMA), often used in sheet form as lightweight or shatter resistance alternative to glass.

Table 3. Runoff coefficients. *Adapted from [11].

Type of Catchments	Coefficients
Ground surface coverings	
- Concrete	0.6- 0.8*
- Acrylic glass(PMMA)	0.6- 0.9
- Plastic sheeting	0.7- 0.8*
- Brick pavement	0.8- 0.9*

A rainwater catchment system design has five (5) primary parameters such as 1) rainfall pattern, 2) water demand pattern, 3) collection area, 4) storage capacity, and 5) system reliability. What influences the rainfall amount is the design of the rain catchment area. The stored rainwater depends on the size of the tank. The model prototype includes the rainfall simulator, the catchment surface, an inlet canal, a filter compartment, circulation ports, storage tank and a cleanout outlet as shown in Fig.7. It has an aluminum frame to support in carrying the model prototype for ease of mobility.

Fig. 7. The RHI model.

The sizing for catchment area helps the designer the provision of the needed supply of drinking water to the public. The slope of the catchment is designed in such a way it will not affect the quickness of the water runoff during rainfall. The minimum slope is 15 degrees. The model used 30 degrees which are the maximum for the efficient running of water through gravity process. The slope affects how quickly water runoff during a rain event.

3.2 RHI Model Dimensional Analysis

The prediction of a prototype behavior from measurements on the model, it must be related to the design, explained by dimensional analysis (DA). The dimensional analysis is defined as the technique that involves the study of dimensions of physical quantities to enables the behavior of large systems from a study of small-scale models [12]. The actual physical flow situation is approximated with a mathematical model, then, experimental measurements are made to check the analytical results. The preliminary results are an essential link in this iterative process. The dimensionless parameters that we obtain are used to correlate data for presentation using the relevance of the expressions in the experiments. In this method, we understand the requirements of physical modeling and its limitation.

The variable in equation 1, V = f (R, A, e) verified by using the volume of rainfall, a footprint of collection surface and efficiency of the collection will explain a result in which Area (A) should be determined in the experiment. In the actual, it is the catchment area that will affect the volume required to harvest rainwater. But for a model, changing the other parameters will show the relationship of correlation. In the model, the water from faucet serves as rain which is determined by adjusting the pressure to get a rainfall scenario as discussed below.

3.3 RHI Rain Simulation

The catchment area shows the amount of water harvested as a function of the amount of runoff created by the rainfall in the area. This runoff, for a defined time scale, is calculated by multiplying a "design" rainfall with a flow coefficient. The simulation for a designed rainfall is carried through a gate valve that controls the water that flows from two (2) spray head assembly to imitate a rainfall. The sprayed water passes through a tray to maintain an equal distance of rainfall. We tried a different method in the rainfall simulation: direct from two shower head flow located at a strategic distance from the farthest top end of the catchment, and the shower head were supported by a tray with equal holes equally distant to imitate rain falling. There were modifications made to the locations of the shower heads during the tests. The locations of the two (2) shower heads directly falling to the catchments are concentrated on their locations only. While the one with a tray that imitates rainfall are falling in such a way as the rainfall do as shown in Fig. 8a. An actual rainfall was also used to get an observation of the rainfall scenario directly from the sky as shown in Fig.8b.

Fig. 8. (a) rainfall simulated from rain tray falling above the catchment; (b) rainfall captured outside

Record of the simulation shows that a rainfall pattern to simulate a different scenario of precipitation such as very wet, wet and dry spells including slow and steady rain ranges from 28 mm3/s, 38 mm3/s, and 56 mm3/s to fill the storage tank. During this process, the model storage tank undergoes leaking due to heat exposure that the glue (a silicon sealant) used starts to shrink and gaps between occurred. The remedy used was to change the type of glue, and the stops the leak.

4. Future Work

This work raises some questions about the rainfall scenarios presented in the experimental rainfall simulation. It raises the question of concept selection using the shower head and not another product such as sprinkler. The inclusion of rain tray provides the benefits of rainfall simulation. The AD theory presented here was viewed to model the relationship between the design information of RHI. The rainfall simulation came into place because the RHI system will require rainfall to work. During the process of modeling, the rainfall scenario partly represented the rain tray with holes to let the water fall into the catchment area from lighter to a heavier fall conveyed through the shower heads, that shows similarity to the actual raindrop which is a limitation of this study, thus will require future study.

5. Conclusion and recommendation

In conclusion, the AD design was able to point out areas where the possibility of error may occur in the system reliability such as leaks at the storage area. For a real infrastructure, rectifying any of the failure modes experienced in the model could be avoided. In the future, when a prototype will be built, those areas identified as weak points shall be observed and to be monitored carefully. Therefore, we were able to model the catchment, to the filter compartment, the disinfectant (chlorination occurs) were identified and correctly set. The RHI model can show in the catchment area rainfall scenarios from heavy, medium to low rainfall. The model can be used to setup a table of dimensions of RHI with costs so as a prospective investor can choose an appropriate size for their budget.

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