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Mathematical realization of diagnosing COVID-19 using Boolean Algebra on an array of colds-related symptoms

Daeuk Kim[1], Maria Nessie Sobina Chiang Yu[2], Ryan Rhay Vicerra[2], Raouf N.G. Naguib[3], Ronnie Concepcion II[2]

[1]De La Salle University, Manila, Philippines/South Korea
[2]De La Salle University, Manila, Philippines
[3]Liverpool Hope University, Liverpool, United Kingdom
Corresponding Email: dae_uk_kim@dlsu.edu.ph

ABSTRACT

COVID-19 has caused countless deaths across the globe. In developing countries like the Philippines, limited access to health services like ICU beds and PCR tests contributed more to COVID-19 related deaths. It is for this reason that the researchers developed a simple COVID-19 diagnostic tool using basic logic gates to determine whether one has COVID-19 or other related illnesses like flu, colds, and allergy. The researchers first collected information regarding the common symptoms of COVID-19 and similar diseases. The identified symptoms cough, fever, fatigue, loss of taste, and smell were used as the inputs for the circuit, while CODI-19 and other related diseases served as the output. The classification of symptoms was divided into often, sometimes, rarely, and never. In order to generate binary digits, often and sometimes were considered positive symptoms (1) while rarely and never were considered negative (0). Minterms were determined through the truth table of the conceptualized circuit. Furthermore, these are used to generate the Karnaugh map. Consequently, simplifying the Boolean expression for each output variable. This is a mathematical realization through Boolean algebra. Through the logic circuit created from Boolean expression, the researchers were able to successfully predict the expected disease based on the existence of symptoms. Furthermore, the researchers were able to translate the circuit into its complementary metal-oxide-semiconductor (CMOS) counterpart. While the designed tool is affordable and can be easily implemented, however, it still possesses a limitation as other COVID-19 positive patients are asymptomatic. Furthermore, the diagnostic tool was not tested on real-world data. Hence, the accuracy of the tool is based on theoretical experiments only.

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INTRODUCTION

The two main keywords that describe the Philippines' health system are decentralization and devolution. Even though the Department of Health (DOH) controls and leads the entire system, the services and facilities of the public hospitals are taken care of by the local government units. This current health system began with the implementation of the local government code in 1991 to provide immediate and specialized medical care to the public but its effectiveness remains in question (Bayani & Tan, 2021). Despite their effort, hospitals in the Philippines are unevenly distributed. There are only ten beds and six doctors available for every 10,000 people, and it is even worse in provincial areas where there is usually only one medicine practitioner per 20,000 patients. Consequently, the medical equipment and supplies are highly limited as well. There have been improvements in terms of medical capacity over the past few years, but it was only beneficial to high-income individuals (Amit et al., 2021).

Because of the common occurrence of typhoons, most of the local government's disaster protocol only focuses on natural disasters such as flooding. When COVID-19 hit the country, the government's first response was travel restrictions and community quarantine which directly affected the average Filipinos (Amit et al., 2021). At the same time, the World Bank predicted the Philippines would experience the largest economic depression among the Southeast Asian countries, and it became a reality. By September of the said year, its economy crumpled by 10 percent which is even worse than the World Bank's prediction. As a result, nearly 3 million Filipinos became poor (Cho, et al., 2021). This also affected the health of the Filipinos because, during the same time, the cost of the RT-PCR test was about 10,000 pesos which are equivalent to 200 dollars. One even needed to go through a strict procedure just to take the test, so most people gave up on taking the test even though they had symptoms of COVID-19 (Bekema, 2021).

COVID-19 is a respiratory illness which is caused by the SARS-CoV-2 virus (World Health Organization, 2022). Meanwhile, severe acute respiratory syndrome (SARS) is a transmittable and viral infection that was first observed in China in 2003 (Smith, 2020). SARS is caused by a group of viruses called coronavirus. Just like the flu, SARS exhibits symptoms such as fever, chills, headache, and diarrhea (Mayo Clinic, n.d.). More specifically, SARS is caused by SARS CoV (Centers for Disease Control and Prevention, 2005). However, it is important to note that flu and SARS are not the same. In relation to COVID-19, the virus causing it is SARS-CoV-2, which is just a mutated form of SARS-CoV. According to the World Health Organization (2022), the symptoms and side effects of COVID-19 range from mild to moderately severe only, without the need for hospitalizations and any special treatments. However, the symptoms are more aggravated for old individuals or those that experience prior diseases such as diabetes and cardiovascular diseases. According to the Philippine Statistics Authority (PSA,2021), the leading cause of death in the Philippines is cardiovascular-related diseases. Furthermore, in a report published by Bloomberg (2021), the Philippines ranked last among 53 countries in terms of pandemic response and resiliency. These two are among the countless reasons for the high hospitalization and death rate in the Philippines. According to the statistics released by the Department of Health (2022), as of February 9, 2022, there are over 50,000 deaths recorded due to COVID-19 cases.

It is for these reasons that a cheaper, yet effective way is needed to overcome this ongoing pandemic. One of the solutions is the use of complementary metal-oxide-semiconductor (CMOS) technology because it is often used in the field of medical diagnosis. In fact, there are several medical devices like lab-on-a-chip devices that are based on CMOS technology to accurately diagnose contagious diseases (Forouhi & Ghafar-Zadeh, 2020).

Objectives

The project aims to provide an alternative medical solution for people who cannot afford to go to the hospital even though they are experiencing covid-like symptoms. With the rising cases of Omicron variant, the symptoms of COVID-19 became more like typical colds and flu which people often have a hard time distinguishing from one another. Thus, developing a logic circuit that predicts disease depending on the occurring symptoms could help the said problem. The transformed CMOS circuit and the stick diagram will be presented as well along with the results of the simulation of the constructed circuit.

METHODS

The methodology consists of three main parts namely conceptualization of the circuit, logic circuit implementation, and lastly complementary metal-oxide-semiconductor (CMOS) circuit and the stick diagram conversion (Fig. 1). The first part describes the initial development of the circuit along with the identification of the inputs and outputs of the circuit. The next part mainly discusses specific methods used in implementing the logic circuit such as the Karnaugh map method. The last part presents the construction of CMOS circuits and corresponding stick diagrams.

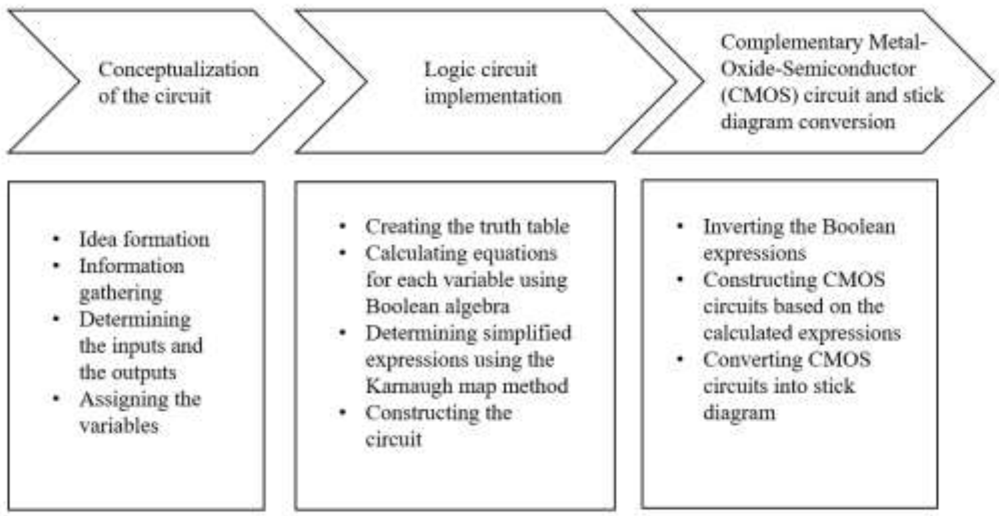


Figure 1. Methodological framework

Conceptualization of the circuit

In order to create the desired circuit, information regarding the common symptoms of COVID-19 and the comparative symptoms of similar diseases were gathered first to select inputs and outputs for the desired circuit. According to the World Health Organization (2020), the most common symptoms of COVID-19 were cough, fever, fatigue, and the loss of taste and smell which are represented by variables C, F, T, and L as inputs. Afterward, a comparative analysis chart of symptoms among COVID-19, flu, colds, and allergies published by the Washington State Department of Health in 2021 was adopted and served as a basis for the output combinations. Output variables W, X, Y, and Z were assigned to represent the diseases. The classification of symptoms was divided into four namely often, sometimes, rarely, and never. Often, and sometimes were considered as positive symptoms while rarely and never were considered as negative symptoms to generate binary digits inputs 0 being negative and 1 being positive.

Logic circuit implementation

Table 1 shows the constructed truth table based on the four most common symptoms of COVID-19 as inputs and COVID-19 and similar diseases as outputs. Based on the truth table, minterms were determined and used to generate Karnaugh maps. Minterms are the product that occupies a specific cell, and it is important to group them to attain the minimized terms or also known as the prime implicants (Crowe & Hayes-GIll, 1998). Simplified Boolean expressions for each output variable, W, X, Y, and Z are the following:

$W = C + F + T + L$ (1)
$X = TL' + FL' + CL'$ (2)

$$Y = F'TL' + CF'L' \quad (3)$$
$$Z = F'TL' + CF'L' \quad (4)$$

Finally, the desired logic circuit was constructed through the Logisim software based on the eq. (1) to (4) as shown in Fig. 3.

Table 1. Truth Table of the conceptualized circuit

C	F	T	L	W	X	Y	Z
0	0	0	0	0	0	0	0
0	0	0	1	1	0	0	0
0	0	1	0	1	1	1	1
0	0	1	1	1	0	0	0
0	1	0	0	1	1	0	0
0	1	0	1	1	0	0	0
0	1	1	0	1	1	0	0
0	1	1	1	1	0	0	0
1	0	0	0	1	1	1	1
1	0	0	1	1	0	0	0
1	0	1	0	1	1	1	1
1	0	1	1	1	0	0	0
1	1	0	0	1	1	0	0
1	1	0	1	1	0	0	0
1	1	1	0	1	1	0	0
1	1	1	1	1	0	0	0

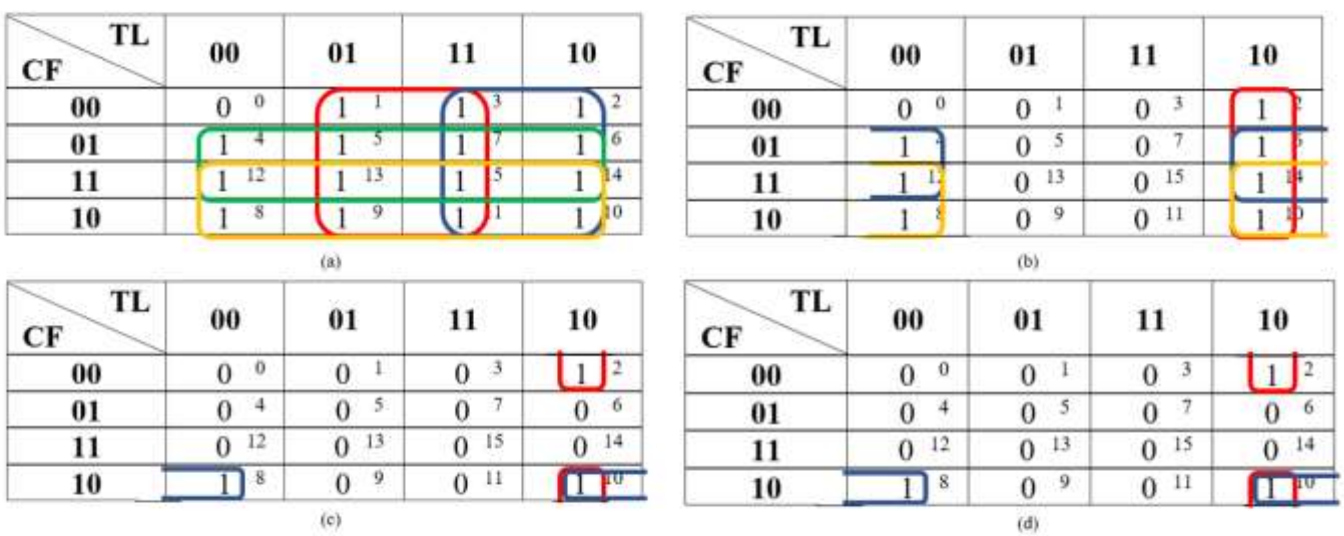


Figure 2. (a) Karnaugh map for W(Covid-19); (b) Karnaugh map for X(Flu); (c) Karnaugh map for Y(Colds); (d) Karnaugh map for Z(Allergies)

Table 2. Grouped minterms and calculated simplified Boolean expression for W

Grouped Minterms	Simplified Boolean Expression
(1,3,5,7,9,11,13,15)	L
(2,3,6,7,10,11,14,15)	T
(4,5,6,7,12,13,14,15)	F
(8,9,10,11,12,13,14,15)	C

Table 3. Grouped minterms and calculated simplified Boolean expression for X

Grouped Minterms	Simplified Boolean Expression
(2,6,10,14)	TL’
(4,6,12,14)	FL’
(8,10,12,14)	CL’

Table 4. Grouped minterms and calculated simplified Boolean expression for Y

Grouped Minterms	Simplified Boolean Expression
(2,10)	F’TL’
(8,10)	CF’L’

Table 5. Grouped minterms and calculated simplified Boolean expression for Z

Grouped Minterms	Simplified Boolean Expression
(2,10)	F’TL’
(8,10)	CF’L’

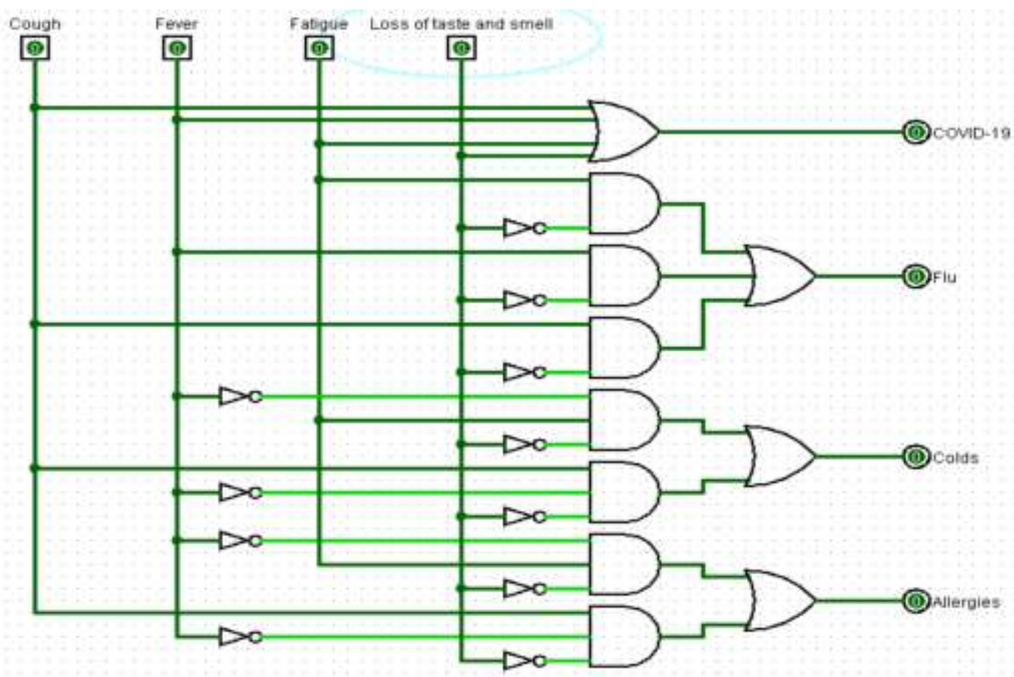


Figure 3. Logic circuit created using Logisim

Complementary Metal-Oxide-Semiconductor (CMOS) circuit and stick diagram conversion

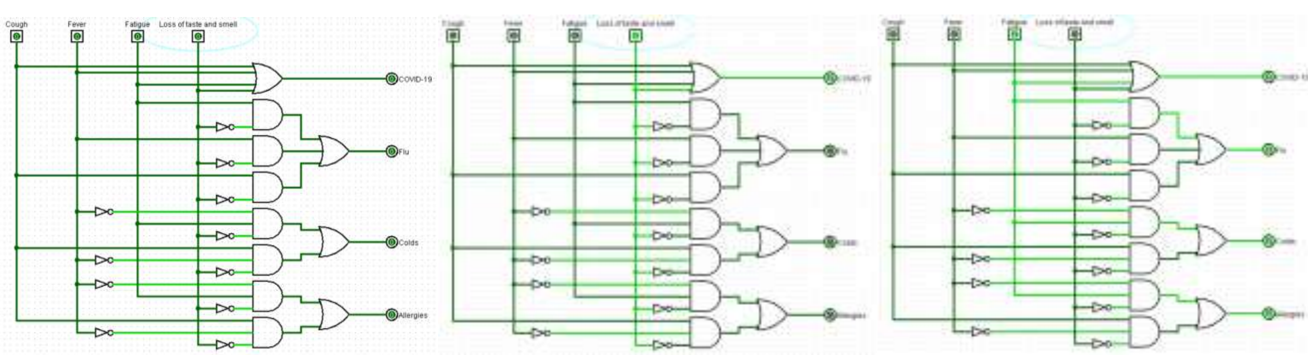
The circuit can further be converted to its equivalent Complementary Metal-Oxide-Semiconductor (CMOS) so that manufacturers can create it easily. This is because as compared to traditional logic gates, CMOS has better capabilities such as temperature stability and less power usage (Liu, 2021). According to Zhang, et al. in 2020, newly developed machines and devices are often required to have compatibility with CMOS. The circuit can be converted to the CMOS through three steps. First step is to acquire the Boolean expression of the function through the Logisim app followed by inverting the Boolean expression. Last step is to generate the CMOS equivalent of the inverse expression. Following are the inverted Boolean expressions:

$$W' = C' + F' + T' + L' \qquad (5)$$
$$X = TL' + FL' + CL'$$
$$X' = T'L + F'L + C'L$$
$$X' = (C + F + T)'L \qquad (6)$$
$$Y = F'TL' + CF'L'$$
$$Y' = FT'L + C'FL$$
$$Y' = (FT' + C'F)L$$
$$Y' = ((C + T)'F)L \qquad (7)$$
$$Z = F'TL' + CF'L'$$
$$Z' = FT'L + C'FL$$
$$Z' = (FT' + C'F)L$$
$$Z' = ((C + T)'F)L \qquad (8)$$

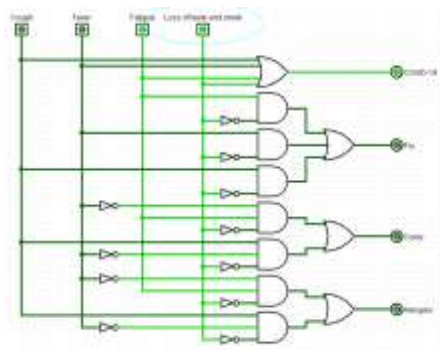
Instead of the usual logic gates, they will now be replaced by transistors, Positive Metal Oxide Semiconductor (PMOS), and Negative Metal Oxide Semiconductor (NMOS) to construct the CMOS circuit. Furthermore, the CMOS circuits can also be represented through the stick diagram. The presentation of the stick diagram of the CMOS circuit is significant because it helps the designer to grasp a general idea of the whole system while also providing the topographical data of the various layers (Oraon & Rao, 2018).

RESULTS AND DISCUSSION

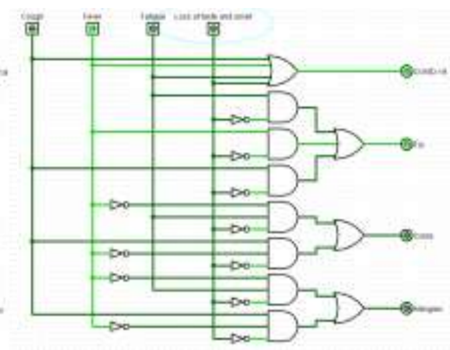
Figure 4 shows the results of the simulation of each combination of input variables and these results correspond to the intended outcome as shown in Table 1. By clicking on the symptoms that the patient is currently experiencing, the output of this circuit shows the possible disease. For instance, if the only symptom is the loss of taste and smell, the patient probably has COVID-19. If the patient is suffering from both fever and fatigue, then it could be either COVID-19 or flu.



(a) *(b)* *(c)*



(d)



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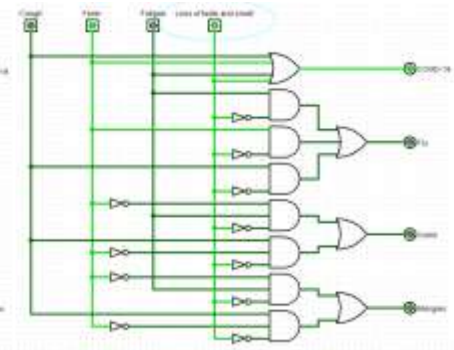
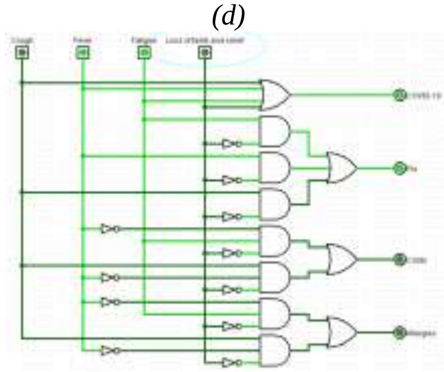
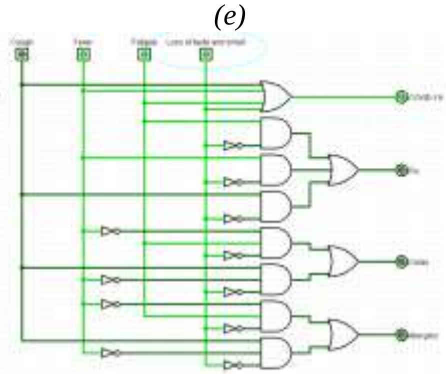


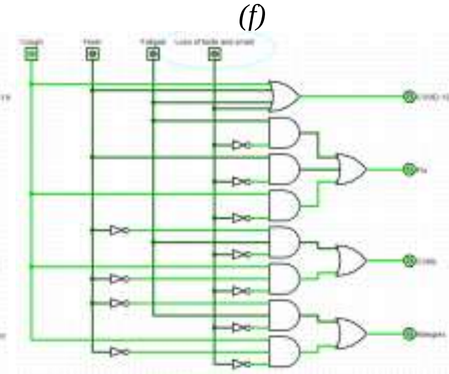
(f)



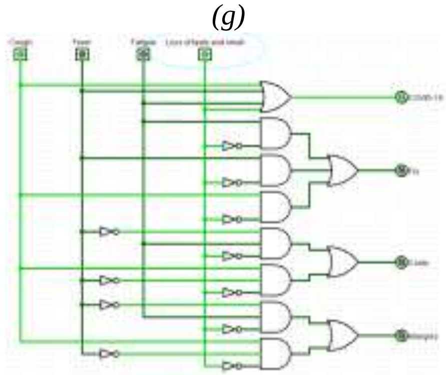
(g)



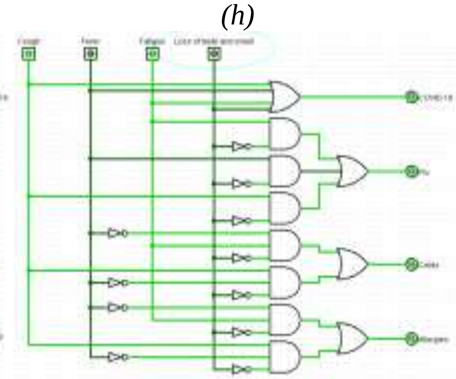
(h)



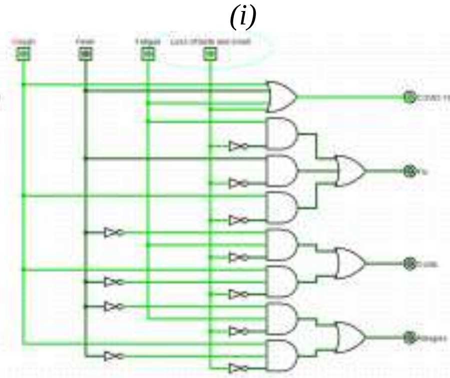
(i)



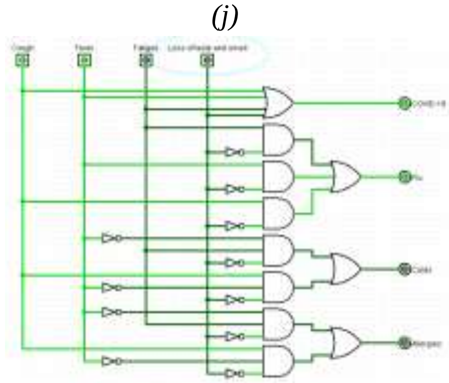
(j)



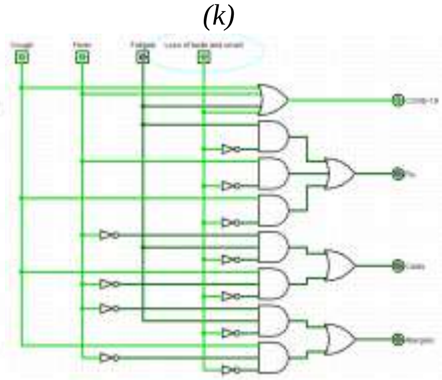
(k)



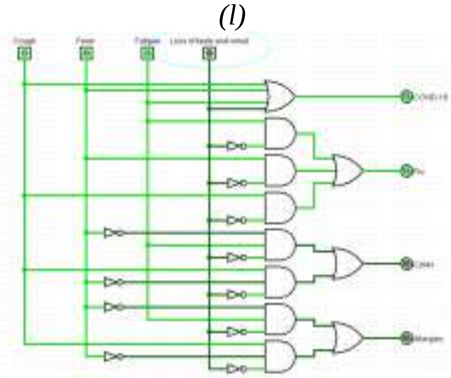
(l)



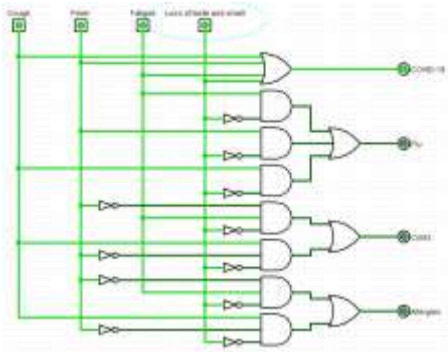
(m)



(n)



(o)



(p)

Fig. 4. Simulation result when (a) C = 0 F = 0 T = 0 L = 0 (b) C = 0 F = 0 T = 0 L = 1 (c) C = 0 F = 0 T = 1 L = 0 (d) C = 0 F = 0 T = 1 L = 1 (e) C = 0 F = 1 T = 0 L = 0 (f) C = 0 F = 1 T = 0 L = 1 (g) C = 0 F = 1 T = 1 L = 0 (h) C = 0 F = 1 T = 1 L = 1 (i) C = 1 F = 0 T = 0 L = 0 (j) C = 1 F = 0 T = 0 L = 1 (k) C = 1 F = 0 T = 1 L = 0 (l) C = 1 F = 0 T = 1 L = 1 (m) C = 1 F = 1 T = 0 L = 0 (n) C = 1 F = 1 T = 0 L = 1 (o) C = 1 F = 1 T = 1 L = 0 (p) C = 1 F = 1 T = 1 L = 1

Through the simulations presented, the inputs for the model blocks are the symptoms of an individual which are cough, fever, fatigue, and loss of taste and smell. Furthermore, the actual process of determining the output (diagnosis), will be based on the tests which are the logic gates presented which are the inverter, AND, and OR gates. Lastly, the output will be the diagnosis of the patient which can either be COVID-19, flu, colds, and allergies. The logic model block of the circuit is presented in Figure 5. Furthermore, Figure 6 shows the designed CMOS circuits based on the constructed logic circuit while Figure 7 represents the stick diagram of each output variable. Figure 8 shows the output waveform of the constructed logic circuit.

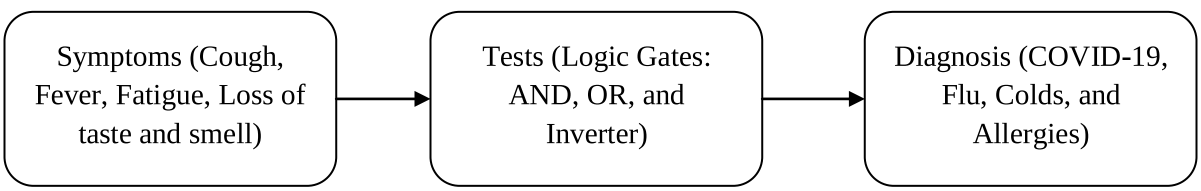
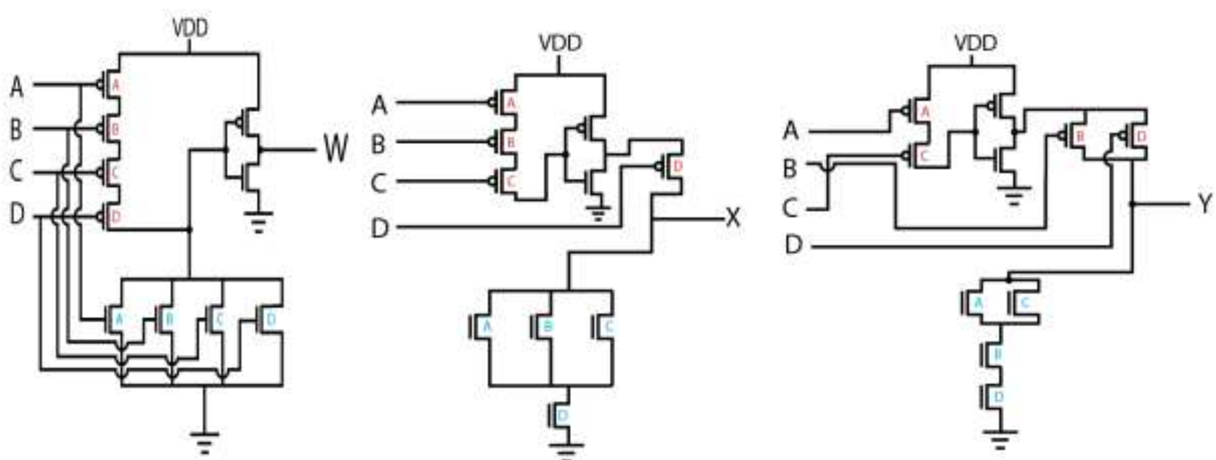
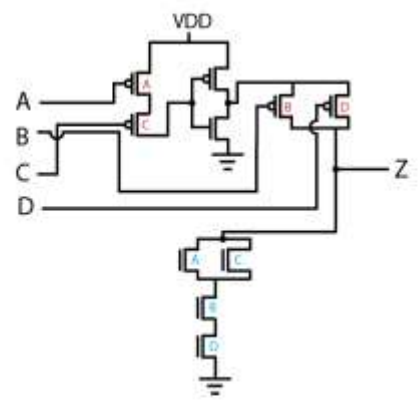


Figure 5. Logic model block of the circuit

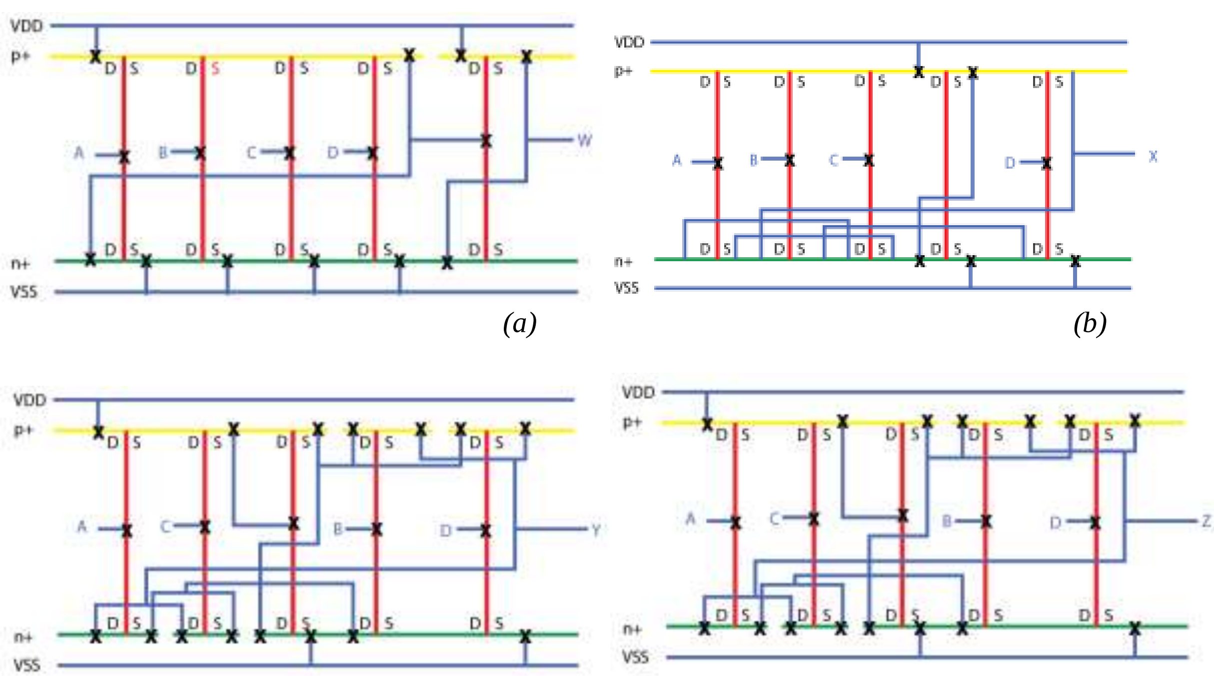


(a) *(b)* *(c)*



(d)

Fig. 6. CMOS diagram of the simulated circuit when (a) output is W (b) output is X (c) output is Y (d) output is Z



(a) *(b)*

(c) *(d)*

Fig. 7. Stick diagrams of the CMOS circuit when (a) W is the output (b) X is the output (c) Y is the output and (d) Z is the output

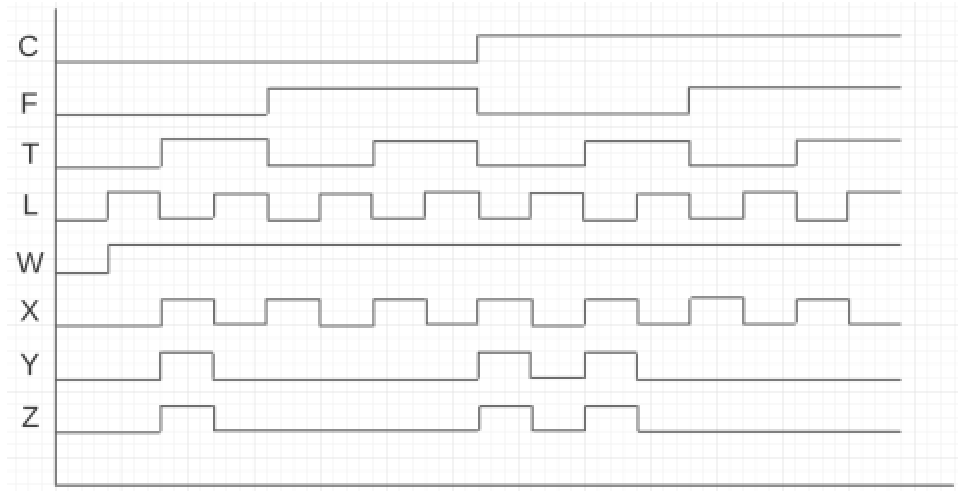


Figure 8. Output Waveform of the constructed logic circuit (Inputs: C, F, T, L; Outputs: W, X, Y, Z)

As presented in Figure 4, the combination of highs and lows in the inputs contributed to the possible diagnosis of whether one has COVID-19 or other related diseases. For instance, if one has a cough, fever, and fatigue, he/she might have COVID-19 or flu. As such, one of the advantages of the designed circuit is that it is simple and can be reused countless times. This contrasts with a normal PCR test, where the stick swab must be replaced after every use. Furthermore, it has contributed to the rise in medical waste since the COVID-19 pandemic (Das et al., 2021).

Among the various ways of simplifying the circuit, the Karnaugh map was used because an optimal minimized Boolean expression can be obtained with a low chance of committing an error. Getting the minimized expressions is significant in designing a circuit because it may reduce the number of components needed to construct the circuit which may lower the cost as well (Aziz, 2020). Also, in terms of visualization, the Karnaugh map is beneficial since its function as a contingency table is effective (Rushdi et al., 2018). In fact, Rushdi and Rushdi in 2018 claimed that the aforementioned method has a great potential to be applied in the medical industry because pseudo-Boolean expression of different clinical data can be easily interpreted using the Karnaugh method. Another study suggested that this method can also be used in advanced data technologies such as quantum dot cellular automata and meta-analysis (Wang & Tao, 2019). However, the device also has limitations. For instance, it doesn't account for COVID-19 patients who are asymptomatic. In statistics released by the Department of Health Philippines, there are over 17,000 cases of active asymptomatic patients as of September 12, 2021 (OCHA Services, 2021). Similarly, there are other COVID-19 symptoms that the logic circuit couldn't account for such as sore throat and diarrhea (Centers for Disease Control and Prevention, 2021). These are among some of the limitations that the designed logic circuit presents.

There are not many studies with regards to detecting COVID-19 using logic gates. As such, the possible comparison of the authors' results with other related publications is limited. However, a study conducted by Pan et al. (2021) constructed an AND logic gate for COVID-19 detection using exonuclease III and DNAzyme as the two inputs. DNAzyme, also known as Deoxyribozyme or Catalytic DNA, are DNA oligonucleotides (Feng and Zhu, 2019). As such, they can perform chemical-specific tasks and analyses (Hengesbach et al., 2008). In medicine, they are usually used as probes for detecting specific chemical strains such as COVID-19 (Mandal, 2019). Consequently, they are widely used in genetic testing and forensics. With this, it can be concluded that Pan et al.'s study is more accurate in detecting COVID-19 than that of the researchers since their studies are dealing with COVID-19 at the molecular level. Similarly, in another study conducted by Pan et al. (2021), they further utilized logic gates to detect the multiple variations of coronavirus diseases such as COVID-19 and SARS, using different coronaviruses as inputs. Furthermore, their study can detect the multiple variations of COVID-19 which are Lambda and Delta. They were able to concatenate different logic gates such as, "And-Or", "Inhibit-And", etc.

Consequently, they were able to show that their constructed design can produce a versatile sensing system while producing minimal false-negative results.

However, even with these limitations presented, the edge of the researcher's design is it can be used by anyone without going to the laboratory since it doesn't deal at the molecular level. As such, making it more affordable and ideal for a developing country like the Philippines, where a lot of its citizens are living on a day-to-day minimum wage. There are a lot of possible extensions from this study. For instance, other researchers might consider placing more symptoms as the input, while at the same time keeping the circuit design optimized. After all, there are a lot of cold-related symptoms, not only the four presented in this study. Furthermore, other researchers might consider constructing a similar approach to detecting similar diseases using logic gates such as differentiating Tuberculosis, Pneumonia, Bronchitis, and other common respiratory illnesses in the Philippines. Here are just some of the extensions which future researchers can do. In addition, future researchers might consider testing the designed circuit using real-world data. COVID-19 is one of the leading causes of hospitalization in the Philippines. As such, workers who can't afford to get tested and treated are forced to succumb to the disease. Because of this, through this paper, the researchers presented a simple logic circuit that can serve as an alternative diagnostic tool for COVID-19 based on symptoms which are cough, fever, fatigue, and loss of taste and smell. However, caution should be observed in using the designed logic gates as some COVID-19 positive patients are asymptomatic, or don't experience any adverse side effects. The designed logic gates will determine whether or not a patient experiences COVID-19, flu, colds, or allergies, based on the combination of symptoms (input). Aside from the practical usability and significance of the designed circuit, the researchers also simplified the circuit into CMOS circuits, so that manufacturers can have an easier time devising it. This is because CMOS has stronger temperature stability which will prevent the overheating of devices. Furthermore, it consumes less power as compared to ordinary logic gates, while producing the same output. Similarly, the researchers were also able to show the stick diagram of the circuits and other skills in digital circuits such as presenting the Karnaugh Map. This approach of using Boolean algebra in formulating classification logic can also be applied to plant root characterization (Concepcion and Dadios, 2021, Concepcion et al., 2021), twin detection (Romanos and Borjac, 2021), binary detection of fish swimming underwater (Almero et al., 2019, Rosales et al., 2021), blood type identification (Rosales et al., 2021), wireless network congestion detection (Alejandrino et al., 2020), leaf disease classification (Lauguico et al., 2020, Bracino et al., 2020), developing new algorithm (Almufti e al., 2021) and photovoltaic maintenance and monitoring (De Guia et al., 2020). If the logic designs, like Figure 7, are perfectly simulated and adhere to the expected standards and expected output, it can be fabricated in a single electronic chip (Ilagan et al., 2020). Consequently, proving that digital electronics has significance in a broad array of applications in a developing world and in ending today's pandemic.

CONCLUSION AND RECOMMENDATION

COVID-19 is one of the leading causes of hospitalization and death in the Philippines. Consequently, there is a need to design a diagnostic tool that is simpler, faster, and more efficient compared to the standard PCR test. The researchers presented a simple logic circuit based on symptoms which are cough, fever, fatigue, and loss of taste and smell. Through their designed logic circuit derived from simplified Boolean expressions, the researchers were able to successfully predict COVID-19 or related diseases through the symptoms presented. Furthermore, the researchers were able to translate their design into its CMOS counterpart. Nevertheless, the researchers weren't able to test its accuracy as a diagnostic tool so testing and validating this circuit can be a path for future researchers to work on.

LIMITATIONS OF THE STUDY

One of the major limitations of this study is the accuracy of the circuit as a diagnostic tool since the circuit was not able to account for all of the cold-related and asymptomatic symptoms. It was not tested against real-world data as well. For the past year, several variants of the COVID-19 virus have emerged, and each variant caused different and distinct symptoms. The product of this study is a simple diagnostic tool based on the most general symptoms of COVID-19 according to the WHO; hence, it may not apply to these variants.

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