Development of logistics library for disaster relief using electric circuit model

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Abstract. In this study, a logistics network simulator based on the similarity between logistic and electric behaviors was considered. To reduce the complexity of practical electrical circuit development, the developed logistics model was converted to an electrical circuit model for analysis. Basic logistics networks such as centralized, de-centralized, and complex models were simulated using the well-defined electrical circuit models. The results show that theoretical logistical behavior can be simulated using electrical circuit models and converted simulation block models, confirming the similarity between flow of logistics and current distribution in electrical circuit.

Keywords: Logistics network, Disaster, Electric Circuit modeling, Similarity

1. Introduction

Natural disaster events have been increasing in recent years, primarily due to global warming and climate change which has impacted lives and economics. The disasters range from localized flooding to huge typhoons and earthquakes [1,2,3]. In particular, flood-related disasters are globally widespread, affecting both urban and rural areas [3,4,5,6]. Recent flooding and landslides in Japan in July 2018 killed and displaced many people living in various prefectures.
around Japan [7]. In July 2015, Myanmar suffered a flood-related disaster due to the torrential rain caused by Cyclone Komen around the Bay of Bengal and the Adman Sea. In these situations, disaster operations played an important role in providing assistance and saving lives. If a nation has strong disaster relief operation procedures, the effect of natural disasters on the population can be minimized. On the other hand, if the nations have weak disaster relief operation procedures, this can increase the loss of lives and the impact on the economy [8]. This has been seen clearly in the cases of 2004 Indian Ocean tsunami and 2011 Tohoku Tsunami. These disasters were similar in some nature, however the Indian Ocean tsunami affected a south east Asia region comprising many developing countries whilst, on the other hand, the 2011 Tohoku tsunami affected the northern region of Japan which is a developed country [9,10]. The resulting devastation from both disasters had two different outcomes. The 2004 Indian Ocean tsunami took over 200,000 lives whereas, the Tohoku earthquake took only 15,000 lives. The main reason for the difference is that most developing countries lack effective prevention and post disaster policies [11].

In recent years, there has been a growing concern about large-scale disasters affecting the safety of our society. However as with many systems, disaster operation systems lack a comprehensive model which could cover most disaster scenarios. This is primarily due to the fact that disasters can occur anywhere and at any time. Due to this unpredictability there is a need for the development of an efficient logistic network. Research has been performed on how to improve disaster operation logistics by focusing on several aspect of emergency relief operations [12,13]. These studies focused on facility location, resource allocation, and evacuation location. In most facility location research, consideration is given to either locating a new building facility or choosing an existing facility for the stocking and distribution of relief items [14,15]. In other studies, the main focus has been on the location and positioning of relief items based on demand [12,16,17,18]. Another area of research is related to optimizing the distribution of relief items or the limited resources to the disaster location [19,20]. Generally, in these works, models were developed and analyzed using the investigated and simulated data [21,22,23,24,25,26]. Clearly, it is necessary to identify the parameters that influence logistic routines or flows. Using the above parameters together with suitable simulation platforms we propose to generate possible logistic flows models. Simulated models were previously developed using mathematical concepts and carried low computational efficiency [27]. These issues occurred due to non-consideration of similarities between real time logistics and the relevant model behaviors. Defining the similarities between logistic flows to non-logistic flows is a complex process, however, identification of such similarities helps to improve the logistic flows when using simulation platforms.

To address this issue, this study developed an electrical circuit model that represents most of the logistical model, taking the similarity between them into consideration [28]. The electrical circuit is the most common simulation area in research because there are several simulation platforms providing options for such research especially for describing the behavior of electrical properties or flows in an electrical circuit. Simulation of electrical current flows can be used to explain the behavior of electrical components such as resistors, capacitors, and inductors. Therefore, the behavior of capacitors and resistors expressed in electrical circuits can be translated to storage tanks and logistics respectively considering their similarity [28].

For the simulation of the logistics network, we initially developed an electrical circuit which described the behavior of the logistics of a centralized model using general electrical
components. The developed circuits were simulated through OrCAD to obtain the theoretical behavior. These electrical circuits were then converted to simulation block models using the MATLAB®/Simulink which is one of the most powerful applications for simulating electric circuits [29]. This application, through its in-built and user-defined library components, provides functions for simulating, optimizing, the provision of statistics, mathematical functions, and data analysis. Further advantages include the ability to break calculations according to the purpose of the block, the ability to change the micro-scale simulation to a larger scale while increasing the block connections, and the ability to define the blocks using existing block library components. Use of block simulation over the algorithm base simulation able to provide the feasibility of developing simulation platforms for the non-professional developers according to their application, easy to identify the errors in the model, and easy to construct simulation models [30][31]. In addition, the development of logistics models with objective functions will also open new areas of study to new entrants in the field of logistics. Additionally, the use of electric circuits enables objective functions such as voltage or current optimization of distribution using the simple circuit models to be realized.

An important parameter that needs to be considered in simulation studies is the step size of the simulation. The use MATLAB block simulation in this study requires the numerical output values to be an integer value of step-size to execute the program. This condition allows the adjustment of the input parameter for the simulation to match with integer values of step-size and it will sometimes lead to limiting the simulation of dynamic disaster situations.

Maintaining the similarity between electrical charge flow and logistic flow, de-centralized and complex networks were also developed in the MATLAB/Simulink platform. The validity of the developed electrical circuits models were compared with the relevant logistics models using theoretical and simulated values.

2. Simulation

As it stated in the introduction section, this study will focus to use the electrical circuit model to express the logistics model. Conversion of logistics model to block simulation was carried out in two step process considering the similarity between the logistics and electric circuits.

2.1. Conversion of logistics model to electric circuit model

![Centralized logistic network model](image)

Figure 1: Centralized logistic network model
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Figure 1 shows the simple centralized logistics network which is considered in this study with the assumed values for the number of people for each disaster area. As shown in Fig. 1, the circled areas represent the distribution (red) and disaster (orange) areas while blue colored arrows represent the branches which include the functions of logistics such as transport delays and storage tanks in disaster areas.

In this study, we consider representing all the commodities in disaster relief logistics using water because of conversion of units. Therefore, through this manuscript water will be used to represent the logistics items unless specify it. Water supply is essential for disaster relief operations. The flow of water supply can be considered to be similar to the flow of electric charge in electric circuits for identifying optimal patterning and flows [28]. In reference [28], we explored the similarity between electric circuits and logistics networks. The supply rate of water from distribution center $W$ can be defined as $W[l/h] = w_R \cdot p$, where $w_R$ is the demand rate of water per person and $p$ is the number of people. This will be considered in relation to distance, truck speed and truck capacity. In the electric circuit model, the current flow can be written as $I_S = Q_{S1} [C/s]$ where, $Q_{S1}$ is the rate of charge flow in the circuit. As the amount of water stored corresponds to the amount of charge stored in a capacitor, it can be described as $Q = C_i V_i [C]$ , $C_i$ is the capacitance and $V_i$ is the applied voltage between the capacitor. In this electrical circuit model, a pulse generator is used as the source and included at the distribution point while the capacitor was placed at the disaster area simulating the water storage tank. The pulse generator simulates the truck operations in logistics model. For the transportation, the distribution time in the branches, or time gap in logistics terms, was provided using an additional delay circuit connected directly at the output of pulse power source.

Initially, the investigation of the logistics network behavior used an electric circuit to determine their similarity. For this purpose, previously stated information was used to develop the equivalent electric circuit model for the centralized logistic network as shown in the Fig. 2.

**Number of nodes 1-8 (R-up1 – R-up8)**

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**Disaster area 1-8 (RL1–RL8)**

Figure 2: Equivalent electric circuit model for centralized logistic model
The components of the electrical circuit were used to simulate the logistic model. In this circuit the distribution center was represented by a pulse generator with the amplitude set to 100 V at 250 Hz, which provides 20 pulses in a 24 ms time period. Active pulse part is corresponding to the amount of charge carried by the pulse, which similar to the capacity of the truck in logistics. And duty cycle of the pulse corresponds to the combination of loading unloading time in logistics networks. As the electrical current flow is similar to logistics flow, the resistance and capacitance values on each of the branch correspond to the logistics information of storage capacity and the number of people at each area. Impedance of the electric circuit and also branches were estimated using the frequency of the pulse, corresponding resistance, and capacitance values for whole electric circuit and its branches. A parallel electric circuit concept was used to distribute the current along the different branches, and its corresponding value depends on the impedance of each branch and its relation can be expresses using Ohm’s law as in equation (1):

$$I_{\text{branch}} = \frac{V}{Z_{\text{branch}}}$$  \hspace{1cm} (1)

Here, \(V\) is the amplitude of the voltage pulse which corresponding to the amount of charge carried in the active pulse \(Q_{\text{pulse}}\) to the connecting node of all the branches in electric circuit similar to the amount of water carried by each truck in disaster relief operation as shown in equation (2). \(I_{\text{branch}}\) is the current corresponding to the node, and \(Z_{\text{branch}}\) is the impedance corresponding to the branch.

$$Q_{\text{pulse}} = \frac{1}{Z_{\text{total}}} \int_{0}^{\text{duty cycle}} V \, dt$$  \hspace{1cm} (2)

The value of capacitor \((C)\) was selected to match the storage capacities of the disaster areas while resistance value, represented by RL in Fig. 2, was selected to represent the number of people in those areas.

A transport delay (Trans-delay) circuit was added to this electrical circuit to delay the pulse similar to the logistics network while its delay time was achieved through the impedance balancing of the R, L and C components within the Trans-delay circuit. Using Ohm’s law to distribute the current matching to the logistics flow, impedance of each branch were used.

For this distribution we used the relation \(I \propto \frac{1}{R}\), where we assigned two resistance values \((R-\text{up(branch)}, R-\text{down(branch)})\) at two ends of the trans delay component to match the impedance as shown in Fig. 2. Resistance values for the \(R-\text{up(branch)}\) and \(R-\text{down(branch)}\) were estimated using the equations (3) and (4) as follows,

$$R - \text{up(branch)} = \frac{1}{P_{\text{node}}} \times 10^{-6} \, k\Omega$$  \hspace{1cm} (3)

$$R - \text{down(branch)} = \frac{1}{(P_{\text{total}} - P_{\text{node}}) \times 10^{-6}} \, k\Omega$$  \hspace{1cm} (4)

where, \(P_{\text{node}}\) and \(P_{\text{total}}\) are nominal values of the number of people at the disaster area and the total number of people affected by the disaster respectively. Considering 1 L in water supply logistics is equivalent to 1 \(\mu\)C in electrical circuit, a multiplication factor of \(10^6\) was used to convert the amount of water supply logistics to electrical charge.

To assign the delay time in the trans-delay circuit component, we assigned impedance in \(k\Omega\) scale and estimated the nominal resistance values using the equation (3) and (4).
Such inclusion of resistance within the trans-delay allows the amplitude of the current pulse to be decreased according to the ratio of the people in the disaster area to the total number of people affected. Charging and discharging through the capacitor occurs due to pulse waveform generator alternating current when the pulse is changing from an on to an off state. Therefore, to maintain the flow of charge in a forward direction, diodes were assigned to this electrical circuit.

2.2. Conversion of logistics equivalent electric circuit model to MATLAB block simulation model

Although the electric circuit model, as initially used, was able to provide the information between the logistic chain and the current flow in the electrical circuit, development of such electrical models are complex process due to the large number of disasters and considering the branches/areas. Hence, this study therefore progressed to use the simulation platform of MATLAB/Simulink to convert the electrical circuits to simple simulation block models.

Figure 3 shows the simulation block model developed using MATLAB®/Simulink library components for a single path of distribution center to disaster area with the relevant conversions. Section A in Fig. 3, represent the supply of logistics to the disaster area using the pulse generator. Terms “In 1” and “In 2” represent the input from the distribution center or the sub-distribution center and input of resources belongs to the disaster area respectively. The information of the pulse amplitude, pulse width, and frequency corresponds to the information of the capacity of truck, loading and unloading time, and number of pulses respectively. As the trans-delay in the electrical circuit delays the pulse, then transport delay was used to delay the pulses in the simulation platform. The integrator used in this model is similar to the combined component of C and RL in the electric circuit. As the time limits of the integrator off-set the time calculations, then the Gain 1 component was used to adjust the off-set values and maintain flow behaviors within the same time domain. In addition, the MATLAB/Simulink model was modified with components including an additional pulse generator and a constant (Constant1) to add an internal pulse generator and capacitor charge respectively. The Switch used in this model is used to terminate the distribution pulse after a certain time period or number of pulses.
3. Results and discussion

3.1. Similarity between electric circuit and logistics

To understand the behavior of logistic flows through the electric circuit model, the centralized model was considered as shown in Fig. 2. The delivery time for each disaster area was estimated using the distance between distribution center and the disaster area along with velocity of the path which was set as 65 km/h. Considering average values for trucks with storage capacity, 10,000 L was assigned as the truck capacity. In addition, the ratio of the number of people in the disaster area versus the total disaster affected people was considered in order to determine the distribution logistics to the disaster areas.

To consider the validity of the simulation we estimated the theoretical values for the logistics model and simulated values in electrical circuit as shown in Table 1. For this analysis we evaluated the percentages of delivery to each node/branch to the maximum distribution pulse using the equation (5).

\[ \text{Percentage of delivery} = \frac{A_{\text{branch}}}{A_{\text{total}}} \times 100 \]  

where, \( A_{\text{branch}} \) and \( A_{\text{total}} \) are the amplitude of the current pulse at a branch and amplitude of total current pulse from the pulse generator respectively. The amplitude of the total current pulse was set to be 3.33 mA with an on-time of 0.3 ms. As shown in the Table 1, the percentage of the delivery to each branch in one pulse in electric circuit closely matched the theoretical values.

To determine the percentage of the delivery at each node, the ratio between people at each node to the total amount of people on the logistics model was used. Electric simulation values presented in Table 1 include the phase delay and amplitude of the simulated current pulse at each branch. These current pulses were plotted against the time as shown in Fig. 4.

Fig. 4 shows the amplitude of the pulses for each of the disaster area (D.A.) with the pulse on-time matching with the theoretically expected amount of charge distributed to each area. The Delay time of each pulse also matched with the theoretically estimated values of delivery time for disaster nodes. These behaviors ensure the validity of the electric circuit model in describing the logistics behavior.

Figure 5 represents the MATLAB simulation block model for the centralized logistics network considering the current flow. As shown in Fig. 5, the pulse generator was used to supply the pulses similar to the electric circuit model as shown in the Fig. 2. Each of the subsystems in the relevant node to disaster area network contains the components as previously explained in the Fig. 3, and transport delivery time is similar to the trans delay in the electric circuit. Gain components used in this simulation block model, is to distribute the total pulse according the amount of people affected at each node similar to the explanation on current distribution in the parallel circuit as shown in Fig. 2.
Figure 4: Pulse patterns obtained from the simulated electric circuit at R-down (branch/disaster area)

Figure 5: Simulation block model for the centralized logistics network using MATLAB®/Simulink

Figure 6: Pulse patterns obtained from the MATLAB/Simulink for centralized model
Table 1: Theoretical estimated values for logistics and simulated electric circuits

| Path of node | Theoretical logistics network | Simulated electric circuit (relate to Fig. 4) |
|--------------|------------------------------|---------------------------------------------|
|              | Distance from the distribution center (km) | Delivery time (ms) | Percentage of the amplitude of the received pulse | Amplitude of current pulse (μA) |
|              | Speed of truck (km/h) | Number of people | Transport delivery (hr) | Percentage from initial delivery (%) |  |
| DC-D.A.1     | 120 | 65 | 15000 | 1.8462 | 17.2 | 1.8462 | 17.25 | 574.44 |
| DC-D.A.2     | 100 | 65 | 25000 | 1.5385 | 28.7 | 1.5385 | 28.73 | 956.71 |
| DC-D.A.3     | 90 | 65 | 15000 | 1.3846 | 17.2 | 1.3846 | 17.25 | 574.44 |
| DC-D.A.4     | 185 | 65 | 5000 | 2.8462 | 5.7 | 2.8462 | 5.72 | 197.14 |
| DC-D.A.5     | 160 | 65 | 6000 | 2.4615 | 6.9 | 2.4615 | 6.91 | 230.01 |
| DC-D.A.6     | 170 | 65 | 8000 | 2.6154 | 9.2 | 2.6154 | 9.19 | 306.03 |
| DC-D.A.7     | 180 | 65 | 8000 | 2.7692 | 5.7 | 2.7692 | 5.72 | 197.14 |
| DC-D.A.8     | 210 | 65 | 8000 | 3.2308 | 9.2 | 3.2308 | 9.19 | 306.03 |
Table 2: Comparison analysis of electric circuit model and MATLAB simulation model

| Number of disaster area (D.A.) | Electric circuit model | MATLAB simulation model |
|-------------------------------|------------------------|-------------------------|
|                              | Amplitude of pulse (µA) | Percentage of delivery (%) | Amplitude of pulse (L/H) | Percentage of delivery (%) |
| 1                             | 574.44                 | 17.25                   | 5747.126                 | 17.24                     |
| 2                             | 956.71                 | 28.73                   | 9578.544                 | 28.73                     |
| 3                             | 574.44                 | 17.25                   | 5747.126                 | 17.24                     |
| 4                             | 197.14                 | 5.72                    | 1915.708                 | 5.747                     |
| 5                             | 230.01                 | 6.91                    | 2298.850                 | 6.896                     |
| 6                             | 306.03                 | 9.19                    | 3065.134                 | 9.195                     |
| 7                             | 197.14                 | 5.72                    | 1915.708                 | 5.747                     |
| 8                             | 306.03                 | 9.19                    | 3065.134                 | 9.195                     |

Figure 6 shows the pulse patterns obtained using the MATLAB simulation model. From comparison of Figs. 4 and 6, it can be seen that the amplitude of the pulse patterns are different in value. However, the percentage of the delivery to each node is similar in value considering the relation state in equation (5). Therefore, the amplitude of the current pulse at each branch and the amplitude of total current pulses was replaced with the amplitude of water supply rate at each node and the amplitude of water supply from the pulse generator as stated in Fig. 5. Table 2 contain the analysis of electrical circuit model and MATLAB simulation model.

As stated in Table 2, the percentages of delivery match with each other including the amplitude of current values and the amplitude of the supply rate of water at each node/branch. However, considering the area of the pulses, the amount of charge carried by the pulse in the electrical circuit model matches the amount of water carried by the pulse in the MATLAB simulation model. Therefore the area under the pulse which equals the amount of charge carried by electric current pulse is similar to the amount of water carried by the distribution pulse in MATLAB simulation. These results confirm that the electrical circuit model matches the simulation block models with correlation between electric charge flow and logistic flow. Further analysis was carried out to validate the developed simulation model match with the electric circuit. Output patterns observed at the each of the disaster areas was compared with the electric circuit model and simulation block model. Figure 7 shows the total amount of charge and water stored at each node/branch versus the time for each disaster area for both the electric circuit model and the simulation block model.

The voltage pattern measured at the capacitor at the electric circuit was converted to charge using the relation $Q_{disaster\ area} = C_{disaster\ area} V_{disaster\ area} [C]$, where, $Q_{disaster}$ is the amount of charge stored inside the capacitor with capacitance of $C_{disaster\ area}$ under applied voltage between capacitor $V_{disaster\ area}$. For this study $1 \ l = 1 \ \mu C$.

The output pattern shown in the Fig. 7, for the electric circuit model and the simulation block model are identical to each other. These observations confirm the developed simulation model using MATLAB/Simulink library can be used to replace the complex electric circuits. To validate these similarities, the delivery time for each of the concepts were analyzed and
Table 3: Comparison of delivery times for logistics, electric circuit model, and MATLAB simulation model for centralized network

| Path of node | Distance (km) | Avg. speed of truck (km/h) | Total delivery time (1 hr = 1 ms) |
|--------------|--------------|---------------------------|----------------------------------|
|              |              |                           | Theory/Logistics | Electric circuit simulation | Simulation model from MATLAB/Simulink |
| DC– D.A.1    | 120          | 65                        | 1.846              | 1.846                    | 1.846                                      |
| DC– D.A.2    | 100          | 65                        | 1.538              | 1.538                    | 1.538                                      |
| DC– D.A.3    | 90           | 65                        | 1.384              | 1.384                    | 1.384                                      |
| DC– D.A.4    | 185          | 65                        | 2.846              | 2.846                    | 2.846                                      |
| DC– D.A.5    | 160          | 65                        | 2.461              | 2.461                    | 2.461                                      |
| DC– D.A.6    | 170          | 65                        | 2.615              | 2.615                    | 2.615                                      |
| DC– D.A.7    | 180          | 65                        | 2.769              | 2.769                    | 2.769                                      |
| DC– D.A.8    | 210          | 65                        | 3.230              | 3.230                    | 3.230                                      |

Table 3 shows the results.
As given in Table 3, the delivery time for each disaster node is the same in order for the logistic model and electric circuit model. The delivery time for the logistics model was estimated using the theoretical logistics information while pulse properties were used for the simulated electric circuit and MATLAB block diagrams.

3.2. Decentralized and complex model behavior in logistics and simulation model

As we discussed in the previous section, the similarity between logistics flow and electrical current flow can be used to develop a logistics simulation model. Considering this development, the simulation model developed using the MATLAB/Simulink is able to convert the electrical circuit for the simulation while providing the feasibility to adjust the logistic relevant information for numerical execution. Therefore, in our study we further analyzed the behavior of the de-centralized and complex logistics network developed using the MATLAB/Simulink library.

For such development, it is necessary to identify that some of the disaster areas which were considered in the centralized logistic network will act as both a disaster area and a distribution center. This criteria was included in the MATLAB/Simulation block model and the model described in the Fig. 3 was modified to that shown in Fig.8.

As shown in Fig. 8, Fig. 3 was modified to include an additional section (section D) to simulate a combined disaster area / distribution point described above. In section C, gain 2 was introduced to assign the percentage of resource going to be used by the disaster area.

The main objective of section D is to generate pulses similar to the truck distribution with the defined parameter values. As the distribution sub-system does not consume all the resources, the addition of the gain 3 components was used to define the percentage of delivery to the next disaster area. The added derivative component provides the means to reverse the process of integration and generation of the pulses. Similar to the mismatch in time domain discussed earlier, the generated pulse from the derivative component also contains a mismatch in pulse width. To adjust the pulse width to compensate for the mismatch in delivery to the next sub-system, gain 4 component was used. With these modifications, simulation models developed from the MATLAB/Simulink were used to observe and validate the similarity between logistic flows and electrical circuit flows. Figures 9 and 10 represent the decentralized model in logistics and its corresponding electric circuit similar simulation block model, respectively.

Figure 8: Basic distribution sub-systemic logistic block model described by electric circuit
For this part of the study, disaster area 1, 2, and 3 were regarded as the areas with dual roles, which act as disaster affected plus sub-distribution to next disaster area. As the decentralized model has options available for routing disaster relief items, these connections make the model more efficient for delivery to the affected area. Moreover, each node (i.e. location) was assigned its own sub-distribution and storage option, as shown in Fig. 8 input line 2 (In 2) in section A. The MATLAB®/Simulink electrical circuit for this model used similar components for the centralized model. Disaster area 1, 2, and 3 are the sub-distribution centers that will distribute the drinking water to their assigned disaster areas. OUT 1 and OUT 2 set in the simulation block model as shown in Figs. 8 and 10 were used in the sub-systems to detect the amount of water stored in the disaster area and the amount of water distributed to preceding disaster areas as a pulse respectively.

As shown in Fig. 9, the percentage of supply to the disaster area 1, 2, and 3 varied from Fig. 1, as these nodes now play a dual role of disaster affected area and also as a sub-distribution area.

**Figure 9: Decentralized logistics network model**

MATLAB®/Simulink
The distribution center was defined considering the number of people affected along the distribution path. Nodes 1, 2, and 3 also defined with percentage values considering the number of people related to each node. Considering these parameters, the developed simulation block diagram is shown in Fig. 10. A numerical simulation was carried for the decentralized model and pulse pattern obtained at each node is shown in Fig. 11.

As shown in Fig. 11(a), amplitude of the pulses at disaster area 1, 2, and 3 in decentralized model is large compared to the centralized model and its comparison is shown in Fig. 11(b). This change occurs due to the total supply from the single distribution center being distributed to the disaster areas 1, 2, and 3 for storage and further sub-distribution. As these disaster areas play a dual role of being disaster affected and also as a sub-distribution area, they hold a percentage of input to their assigned disaster areas. Disaster areas 4 – 8 receive the same amount of supply rate compared to the centralized model. In addition, the transport delivery times for the theoretical and the simulation model are of similar values. This information is presented in Table 4 for further reference.

Figure 11: (a) Pulse patterns obtained from the MATLAB/Simulink for decentralized model and (b) comparison of amplitude for D.A.1, D.A.2, and D.A.3 between centralized and decentralized model
Table 4: Comparison between theoretical calculation and simulation of decentralized model

| Path of node | Distance (km) | Avg. speed of truck (km/h) | Total distribution time (hr) | Amplitude of the pulse (L/hr) |
|--------------|--------------|---------------------------|-----------------------------|------------------------------|
| Theory       | Simulation   |                           | Theory                     | Simulation                   |
| DC– D.A.1    | 120          | 65                        | 1.8461                      | 1.8461                       | 7662.835                    |
| DC– D.A.2    | 100          | 65                        | 1.5384                      | 1.5384                       | 14942.529                   |
| DC– D.A.3    | 90           | 65                        | 1.5384                      | 1.5384                       | 10727.969                   |
| D.A.1– D.A.4 | 65           | 65                        | 2.8461 (1+1.8461)           | 2.8461                       | 1915.709                    |
| D.A.2– D.A.5 | 60           | 65                        | 2.4614(0.9230+1.5384)       | 2.4614                       | 2298.851                    |
| D.A.2– D.A.6 | 75           | 65                        | 2.6922(1.1538+1.5384)       | 2.6922                       | 3065.134                    |
| D.A.3– D.A.7 | 90           | 65                        | 2.7692(1.3846+1.3846)       | 2.7692                       | 1915.709                    |
| D.A3– D.A.8  | 130          | 65                        | 3.3846(2+1.3846)            | 3.3846                       | 3065.134                    |

As stated in Table 4, the distribution times for disaster areas 1 – 3, are similar values to the centralized model. The decentralized model maintains direct connection between main distribution center and nodes 1 – 3 and hence the values are of similar order. However, route options between disaster nodes 1 – 3, and predecessor nodes 4 – 8, contain different distances between each other compared to the centralized model therefore resulting in different distribution times.

Figure 12 represents the complex logistics network used in this study to develop the MATLAB block simulation model. As complex logistics structures contain one or more interconnection between nodes, it is necessary to consider such information when developing a simulation block model. Considering the simulation blocks from the centralized and decentralized models, a complex simulation model was developed as shown in Fig. 13.
As shown in Fig. 13, extra time-delay components were added into the simulation block model for disaster nodes. These disaster nodes contain more than one interconnection between disaster nodes. A numerical simulation was carried out for the complex simulation block model as shown in Fig. 13. The supply pulse at each disaster area and total water supply at each disaster area was plotted as shown in Fig. 14 and Fig. 15 respectively. Note the Fig. 14, pulse shapes differ from the single pulse shape previously discussed for the disaster area marked 5, 6, and 8. This anomaly of pulse shape occurred due to mix of more than one pulse with different distribution delays for considered routes. As we considered the number of people for each distribution line as a benchmark in deciding the percentage of main distribution to each node, then the area of each pulse should represent the amount of supply equivalent to number of people. Such analysis was carried out to confirm the validity of the model and the results are shown in Fig. 15.

Figure 13: Simulation block model for complex logistics network using MATLAB®/Simulink

Figure 14: Pulse patterns obtained from the MATLAB/Simulink for complex model
As shown in Fig. 15, the amount of total supply after 24 for each disaster area node is similar in value compared to Fig. 7(b) in centralized model. However, the pattern of distribution changes for nodes 5, 6, and 8 due to mix of input pulses coming from different sub-distribution nodes. This information is summarized and tabulated in Table 5 for further reference.

Theoretical values indicated in Table 5 are from the estimation of values using the available logistics information, while simulation values were obtained from the distribution patterns from the MATLAB block simulation.

4. Conclusion

In this study, we investigated and validated the behavior of a logistics network using electrical
circuits considering their similarity. For this purpose, we considered the logistic water supply flow as an electric charge. General electrical circuit components such as resistors, capacitors, pulse generator, and trans-delays were used to develop an electrical circuit to represent the logistics network. A combination of the electrical circuit parts were connected to represent the main components of disaster relief logistics network known as distribution centers, distribution nodes, and disaster areas. To reduce the complexity of the electrical circuit model especially for developing large and complex logistics, these electrical circuits were converted to the block-circuit models using the MATLAB®/Simulink library. A basic logistics network for centralized, de-centralized, and complex scenarios were developed and simulated in this study.

Simulated results for electrical circuits and simulation block models were observed to be similar in shape to the theoretical logistics values. The analysis of the delivery time for transportations of disaster relief goods and electrical pulses are similar in the order in all the logistics similar simulation block models.

Decentralized and complex logistics models utilized some of the nodes as dual role disaster area which act as sub-distribution nodes causing a change in the amplitude of the input pulses due to their dual mode. However, these dual mode nodes distribute onwards a percentage of what is received considering the number of people in the distribution path.

The study demonstrated that we were able to provide same amount of supply to all the disaster areas irrespective to the logistics model. This information confirms that the behavior of logistics supply chain can be simulated using the electric circuit model.

In our future work, this investigation will be expanded further to include the introduction of warehouses at dual role disaster sub-distribution areas and third party logistics providers to improve the logistics model for develop practical logistics model for disaster relief operation.

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