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Simulating Transport Capacity, Delivery Speed, and Routing Efficiency to Predict Economic Growth

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Abstract

This study uses a simulation-based approach to investigate the impact of delivery delays due to constraints on transport capacity, transit speed, and routing efficiencies on an economy with various levels of interdependency among firms. The simulation uses object-oriented programming to create specialized production, consumption, and transportation classes. A set of objects from each class is distributed randomly on a 2D plane. A road network is then established between fixed objects using Prim's MST (Minimum Spanning Tree) algorithm, followed by construction of an all-pair shortest path matrix using the Floyd Warshall algorithm. A genetic algorithm-based vehicle routing problem solver employs the all-pair shortest path matrix to best plan multiple pickup and delivery orders. Production units utilize economic order quantities (EOQ) and reorder points (ROP) to manage inventory levels. Hicksian and Marshallian demand functions are utilized by consumption units to maximize personal utility. The transport capacity, transit speed, routing efficiency, and level of interdependence serve as 4 factors in the simulation, each assigned 3 distinct levels. Federov's exchange algorithm is used to generate an orthogonal array to reduce the number of combination replays from 3^4 to just 9. The simulation results of a 9-run orthogonal array on an economy with 6 mining facilities, 12 industries, 8 market centers, and 8 transport hubs show that the level of firm interdependence, followed by transit speed, has the most significant impact on economic productivity. The principal component analysis (PCA) indicates that interdependence and transit speed can explain 90.27% of the variance in the data. According to the findings of this research, a dependable and efficient regional transportation network among various types of industries is critical for regional economic development.

Keywords

Vehicle Routing Problem, Minimum Spanning Tree, Trucks, Road Networks, Production Functions, Modelling of Transport Systems

1. Introduction

An economy is a complex system of interrelated production, consumption, and exchange activities that ultimately determines how scarce resources are allocated among all the stakeholders [1]. Transport systems play a vital economic role by channeling goods between supply and demand. The system comprises of transport assets (trucks, trains, barges, planes) and networks (roads, railways, rivers, and air corridors). The total volume of goods transferred between various supply and demand points is based on the number of transport assets, carrying capacity of each asset, speed of delivery, distance, etc. An efficient transport system is an amalgamation of public and private interests. Investment in a transport asset by a private enterprise requires consideration of a variety of factors, including the opportunity cost of capital, utilization factor, market price, demand, service rate, an average reduction in lateness, fixed costs (storage), and variable costs (fuel, wages, maintenance, toll). Sole investment in transport assets does not guarantee an optimal increase in freight volume in the absence of a reliable network.

An Input-Output analysis identifies production flow among the various sectors in the economy to the final consumption [2]. For example, Lithium Carbonate production from ore Spodumene utilizes feeds like natural gas, sulfuric acid, lime, hydrogen peroxide, sodium carbonate, etc. as inputs. The finished product is then used in the production of lithium-ion batteries, ceramics, greases, chemicals, pharmaceuticals, rubbers, and metallurgical industries [3]. The interdependence of industries on each other's production makes it vital that the industry's output is moved effectively and efficiently across the supply chain to avoid the formation of bottlenecks that can hinder an economy's growth potential.

2. Problem Description

The world lacks universal access to efficient transportation systems. According to a study by the World Bank, there is a strong correlation between the length of paved roads in a country and its gross domestic product. The average density of paved roads in high-income economies is 10,110 km per million inhabitants, 1660 in average income, and only 170 in low-income economies [4]. Despite their wealth in natural resources, countries such as Mali, Senegal, Benin, Congo, Afghanistan, Liberia, Vietnam, and Peru lack reliable transportation systems [5]. Many of these areas have a high density of unpaved dirt roads, making travel extremely dangerous due to road narrowness, flooding, landslides, rock falls, erosion, and the operational use of outdated transport that frequently breaks down during transit. The combination of poor road conditions and unreliable transportation equipment makes the transfer of goods extraordinarily cumbersome and time-consuming. As shown in **Table 1**, the timeliness of freight deliveries in these regions lags far behind that of the developed world. The timeliness of freight delivery in Sierra Leone is only 53.30% of that of Germany. There is also a significant difference in gross national income (GNI)-per capita between developed and impoverished regions, with Ghana (GNI)-per capita being only 8.98% of that in Germany. An efficient transportation system is essential for increasing regional GDP levels; however, given the high cost of building and maintaining various transportation systems, there is a need to analyze how various forms of transportation system improvements affect GDP levels while considering the complexities of the regional supply chain.

Table 1. 2018 Logistics Performance Index (LPI) of various countries [6].

Country	GNI/Capita [7]	LPI Score	LPI Infrastructure	Logistics Competence	Timeliness
Germany	$58,070	4.20	4.37	4.31	4.39
Sweden	$56,220	4.05	4.24	3.98	4.28
Japan	$44,370	4.03	4.25	4.09	4.25
United States	$63,780	3.90	3.51	3.87	4.08
France	$49,200	3.84	4.00	3.84	4.15
Ghana	$5220	2.57	2.44	2.51	2.87
Pakistan	$4770	2.42	2.20	2.59	2.66
Guinea	$2510	2.20	1.56	2.07	2.04
Gabon	$14,110	2.16	2.09	2.07	2.67
Sierra Leone	$1580	2.08	1.82	2.00	2.34
Angola	$6500	2.05	1.86	2.00	2.59
Afghanistan	$2100	1.95	1.81	1.92	2.38
Papua New Guinea	$4190	2.17	1.97	1.88	2.44

LPI Infrastructure—Quality of trade and transport-related infrastructure; Logistics Competence—Competence and quality of logistics services; Timeliness—Timeliness of shipment in reaching the destination within the scheduled or expected delivery time.

Problem Statement

Given an economy with n firms, each of which requires m inputs of raw materials to produce a finished good, and where $m = (1, 2, 3, \cdots, n-1)$ denotes the final outputs of other firms:

1) What is the relationship between productivity[1] & transport capacity?

2) What is the relationship between productivity & speed of freight travel?

[1]Units of finished outputs.

3) What is the relationship between productivity &efficiency of routing?

4) How does the level of interdependence among firms affect economic productivity in the presence of an inefficient transport system?

The transport system implemented in our study is the trucking industry and road networks. The trucking industry's selection over other systems has been primarily due to it being the primary freight mover across multiple regions globally [8] [9].

3. Model and Formulation

Modeling the effects of an inefficient truck-road transport system on a dynamic economy requires integration of various concepts, including object-oriented programming [10], graph theory, operations research, micro/macroeconomics, and system analysis, etc. The resultant platform allows a user to distribute a combination of production and consumption nodes over a two-dimensional area. The nodes are connected to each other by the application of a minimum spanning tree to simulate a road network, with additional edges added to create close loops. The production nodes are classified into mining and manufacturing sectors with each sector sub-categorized into different types and with each type holding multiple clones. Production nodes continuously monitor the market conditions, including cost of intermediaries[2] and respond by varying scales of production per a cost minimization or profit maximization strategy [11].

The consumption points in the economy are simulated as market centers which facilitate trade of finished products between customers and manufacturers. The service rate of customers at each market is based on the corresponding number of service stations present. Market centers use cost minimization strategy to calculate the amount of land, labor and capital required to maintain a minimum number of service stations such that the customer traffic intensity factor < 1.0 [12]. The customers are a sub-class of market objects introduced in the simulation during the trading phase. Each customer is loaded with a minimum utility value of consumption, a varying spending budget, and a table of utility coefficients allotted to the consumption of each commodity. Marshallian and Hicksian demand functions are implemented to simulate the consumption of commodities at the customer level [11] [13].

The production process in the simulation is a multistep process starting with resource mining, followed by delivery of ores from mines to industries for refining (Tier 1), followed by the transfer of refined products to manufacturing firms (Tier 2) for further value addition and ultimate transfer of finished products to markets for customer consumption [14]. A finished commodity can go through multiple tiers of value addition at numerous production sites before finally making its way to the market. Each tier utilizes a different set of intermediaries during the production process. These intermediaries are basically outputs of other industries in the simulation. The production process is sensitive to the

[2]Raw materials that are 100% consumed during a production run.

availability of intermediaries since a firm terminates production when one of the intermediaries falls below a critical level.

Transport hubs are an extension of the main class that are supplied with a set of subservient transport units. Transport hubs are integrated with the minimum spanning tree network with responsibility of collecting pick up-drop off orders generated by various production and consumption nodes, followed by route planning for transport units. Transport hubs operate in binary states of *idle* or *active*. An *idle* state corresponds to all trucks of a corresponding hub being located at the hub. This activates a search mechanism where the hub checks on the binary value of reorder variable at various production and consumption nodes. Given that a node's reorder value is "1", the hub checks the binary value of the "order in" variable on all the corresponding input feeds. The hub collects source, sink, container, quantity, and order cost information given a feed's "order in" state is "0". The source specifies the global id of the node where feed is being procured from, the sink indicates the global id of node where the feed is getting delivered to, the container indicates which one of the input feeds is being replenished at the sink, quantity indicates the volume of product that is being moved between source and sink and is the minimum value of economic order quantity (EOQ) and truck carrying capacity, order price is the combined cost of product purchase and freight costs.

Upon initialization, the simulation runs an interdependent protocol that links various supplier nodes to production and consumption nodes based on the criteria of minimum distance. Feed quantities are checked at the conclusion of each shift, and a reorder signal is generated if a given feed level falls below the reorder point. The simulation continuously runs an interdependent protocol that continuously updates the supplier options based on product availability and minimum combined cost of product and freight. Sale price of a product by a given firm is determined based on the maximum value of either the cost of production or the market price determined by Walrasian stability equilibrium [11]. The economic order quantity (EOQ) and reorder point (ROP) is updated for a given feed upon selection of a new supplier.

Transport hubs initiate a vehicle routing problem solver upon receiving a list of pick up-drop off delivery orders. The vehicle routing problem protocol uses combinatorics to sequence a set of deliveries to minimize the total distance covered by all the corresponding vehicles. Each vehicle is loaded with a drive plan derived using Floyd Warshall matrix that defines a set of waypoints on the minimum spanning tree that the vehicle must traverse between hub departure, execution of pickup-drop off deliveries, and arrival back at hub. The freight price per hub is dynamic in nature and calculated based on the utilization factor of transport assets.

The interest rate in the economy on lending and savings is dynamic and is calculated using the ISLM model [15] [16]. The overall state of the economy is tracked using various indices including Fischer index, Real-Gross domestic product, Nominal-Gross domestic product, volume of stockouts (shortages), rate of production and rate of consumption, etc. [17] [18] [19].

3.1. Derivation

3.1.1. Object Oriented Programming

Object-oriented programming has been used in our simulation to model real world systems. One of the significant advantages of object-oriented programming is the ability to reuse classes through inheritance and polymorphism techniques. Inheritance allows a child class to inherit the identical functionality of a super class and then add its own functionality. Polymorphism allows for overriding defined method, causing each object to behave differently when the inheritance is invoked [20].

Let ℂ() be a special class comprised of constants $c_1, c_2, \cdots, c_n$, variables $r_1, r_2, \cdots, r_n$, and functions $fx_1, fx_2, \cdots, fx_n$ [10]. Let $T = \{t_1, t_2, \cdots, t_n\}$ be a set of unique commodity types in the economy. For each commodity type $t_i \in T$, let there be p production units. The array of production units can then be represented by $I = \{p_0^{t_1}, p_1^{t_1}, \cdots, p_z^{t_n}\}$, where z represents the total production units in the economy. Let $M = \{m_1, m_2, \cdots, m_n\}$ be an array of consumption units and $L = \{l_1, l_2, \cdots, l_n\}$ be an array of transport hubs in the economy. Arrays $\{I\}, \{M\}, \{L\}$ represents objects of special class ℂ(), where total number of objects in simulation is given by $\Theta : \Theta = \{n \mid n \in \mathbb{C}, 0 < n \le M + I + L\}$

3.1.2. Modified—Prim's Minimum Spanning Tree

Prim's algorithm is used to build a minimum spanning tree that connects all fixed nodes to form a network that mobile units can use to traverse 2D space. The prim-heap version of the algorithm runs in $O\left[m + nlognlog\left(\frac{2m}{n}\right)\right]$ time.

Input: A digraph G with vertices $V(G) = [1, \cdots, n]$

Output: (1) A subset of the edges that connects all vertices, such that the total weight (distance) of all the edges in the tree, is minimized.

(2) Modification—A subset of new edges* that connects all vertices of degree 1 ∈ MST (1): total weight of new edges* is minimum.

Prim-Heap Algorithm [21]

Select an arbitrary vertex s

for each neighbor u of s; set $near(u)$ to $w(u,s)$, the weight of the edge (u,s)

All other vertices have their $near$ value set to "∞"

Add the other $n-1$ vertices as follow:

1. Find the vertex v not in G with a minimum near value
2. for each neighbor u of v

   if ($w(u,v) < near(u)$ and u not in T)

   then $near(u) \leftarrow w(u,v)$;
3. Add v to G

Creating cycles

for each v of G, create a set $[1,\cdots,m]$ of v where degree = 1
Rerun: Prim-Heap Algorithm.

3.1.3. Floyd Warshall Shortest Path

The Floyd Warshall algorithm is used to construct an all-pair shortest path matrix. The vehicle routing problem solver uses the matrix to estimate optimal routes for various deliveries.

Input: A digraph G with vectors and distances $c: E(G) \to \mathbb{R}$
Output: An $n \times n$ matrix M such that $M[i, j]$ contains the length of the shortest path from vertex i to vertex j

$M[i, j] := \infty \quad \forall i \neq j$ (*Minimum distances initialized as infinite*)
$M[i, j] := 0 \quad \forall i$
$M[i, j] := c((i, j)), \quad \forall (i, j) \in E(G)$
for i := 1 to n do
  for j : = 1 to n do
    for k := 1 to n do
    if $M[j,k] > M[j,i] + M[i,k]$ then $M[j,k] := M[j,i] + M[i,k]$
for i:= 1 to n do
    if $M[i,i] < 0$ then return ('negative cycle found') [22]

3.1.4. Production Function

A production function is a mathematical equation that provides a technological relationship between a production process's outputs and corresponding inputs with the principal task of estimating substitution among various factors of production to achieve a particular output level [23].

Consider a production function that utilizes technology (A), labor (L), land (B), and capital (K) as inputs to produce an output (Q): $Q = AL^p B^q K^r$

The associated cost of production C can be written as $C = Lw + Bx + Ky$, where p, q, r are exponents of inputs, and w, x, y are respective costs of inputs. The total revenue (R) and profit (π) from sales of (Q) units at market rate (M_p) with a variable cost factor (V) can be written as:

$$R = QM_p, \quad \pi = R - C - V(Q)$$

1) profit maximization

The unconstrained profit maximization function can be written as:

$$\text{maximize } \pi = Mp(Q) - C - V(Q)$$

$$\pi = Mp\left(AL^p B^q K^r\right) - \left(Lw + Bx + Ky\right) - V\left(AL^p B^q K^r\right)$$

$$\text{s.t}: Mp > V, p > 0, q > 0, r > 0$$

Taking a partial derivative of L, B, and K with respect to π:

$$\frac{\mathrm{d}\pi}{\mathrm{d}L} = M_p\left(ApL^{p-1} B^q K^r\right) - w - ApL^{p-1} B^q K^r V = 0$$

$$\frac{\mathrm{d}\pi}{\mathrm{d}B} = M_p\left(AL^p qB^{q-1} K^r\right) - x - AL^p qB^{q-1} K^r V = 0$$

$$\frac{\mathrm{d}\pi}{\mathrm{d}K} = M_p\left(AL^pB^qrK^{r-1}\right) - y - AL^pB^qrK^{r-1}V = 0$$

Solving for *L*, *B*, *K*

$$L = \left[Ap\left(\frac{L^pB^qK^r}{L^p}\right)\left(\frac{M}{w} - \frac{V}{w}\right)\right]^{\frac{-1}{p-1}}$$

$$B = \left[Aq\left(\frac{L^pB^qK^r}{B^q}\right)\left(\frac{M}{x} - \frac{V}{x}\right)\right]^{\frac{-1}{q-1}}$$

$$K = \left[Ar\left(\frac{L^pB^qK^r}{K^r}\right)\left(\frac{M}{y} - \frac{V}{y}\right)\right]^{\frac{-1}{r-1}}$$

The maximum output level Q^* for maximum profit π^* can now be calculated by solving simultaneous equations for (*L*), (*B*), (*K*).

2) cost minimization

The production cost minimization function can be written as:

$$\min C = Lw + Bx + Ky \ \ \text{s.t}: AL^pB^qK^r = Q_{\min}$$

Writing Lagrange of the above function:

$$\mathcal{L} = Lw + Bx + Ky + \lambda\left(Q_{\min} - AL^pB^qK^r\right)$$

Taking a partial derivative of *L*, *B*, and *K* with respect to $\mathcal{L}$;

$$\mathcal{L}_L = w - ApL^{p-1}B^qK^r\lambda = 0; \ \mathcal{L}_B = x - AL^pqB^{q-1}K^r\lambda = 0$$

$$\mathcal{L}_K = y - AL^pB^qrK^{r-1}\lambda = 0; \ \mathcal{L}_\lambda = Q_{\min} - Lw + Bx + Ky = 0$$

Solving for *L* and *K*:

$$\frac{w}{x} = \frac{ApL^{p-1}B^qK^r\lambda}{AL^pqB^{q-1}K^r\lambda} \Rightarrow L = \frac{Bpx}{qw}; \ \frac{x}{y} = \frac{AL^pqB^{q-1}K^r\lambda}{AL^pB^qrK^{r-1}\lambda} \Rightarrow K = \frac{Brx}{qy}$$

Solving for *B*:

Substituting the value of *L*, *K* into the production function

$$Q = A\left(\frac{Bpx}{qw}\right)^p B^q \left(\frac{Brx}{qy}\right)^r$$

$$Q = A\left(\frac{px}{qw}\right)^p \left(\frac{rx}{qy}\right)^r B^{q+p+r}$$

$$\frac{Q}{A}\left(\frac{px}{qw}\right)^{-p}\left(\frac{rx}{qy}\right)^{-r} = B^{q+p+r}$$

$$B^* = \left(\frac{Q}{A}\right)^{\frac{1}{p+q+r}}\left(\frac{px}{qw}\right)^{\frac{-p}{p+q+r}}\left(\frac{rx}{qy}\right)^{-\frac{-r}{p+q+r}}$$

$$L = \frac{B^*px}{qw}, \ \ K = \sqrt[r]{\frac{Q}{AL^pB^{*q}}} \qquad [11]\ [24]$$

3.1.5. Customer Demand

Important contemporary consumer demand functions *i.e.*, the Hicksian and Marshallian demand functions, have been implemented to simulate the demand of various commodities in our simulation. The formulation of both functions is as follows:

Let $E=\{e_1,e_2,\cdots,e_n\}$ be an array of customers in the economy. Customers E is an array of unique objects $\mathbb{N}=\{n \mid n\in\mathbb{C}, 0<n<E\}$, where $E\gg I$ and I is the total number of firms.

Input: Given a customer $e\in\mathbb{N}$ with a consumption bundle $W=\{t_1,t_2,\cdots,t_n\}\subset T$ with corresponding consumption utilities $U=\{u(t_1),u(t_2),\cdots,u(t_n)\}$, corresponding prices $P=\{p_1,p_2,\cdots,p_n\}$, budget M, minimum utility $U_{\min}$ and savings level S

Output: Find bundle quantities $Q=\{q_1,q_2,\cdots,q_n\}\in W$

1) Hicksian

$$\text{Minimize } C=\sum_{i=1}^{n} q_i p_i$$

$$\text{subject to}: \prod_{i=1}^{n} q_i^{u_i}=U_{\min}$$

2) Marshallian

$$\text{Maximize } U=\prod_{i=1}^{n} q_i^{u_i}$$

$$\text{subject to}: \sum_{i=1}^{n} q_i p_i \le M$$

3.1.6. Supplier Selection

In the simulation, production firms transform intermediate and raw materials that other firms supply into finished goods that are then sent to other firms for value-addition or end-use. Given that the simulation firms are dispersed throughout a 2D plane, a company must buy its feeds from the source locations, resulting in the lowest combined transportation and raw material costs.

Input: Given a demand point $\mathrm{d}\in\Theta$

Bucket index $b_j^t\in B$ where $B=(t_1,t_2,\cdots,t_n)$

Demand quantity $I_{\mathrm{d}}\in\mathrm{d}$,

Set of suppliers S:

$$S=\begin{cases} n \mid n\subseteq\Theta, 0<n\le I & \mathrm{d}\in M \\ n \mid n\subseteq\Theta, 0<n\le I-t & \mathrm{d}\in I \end{cases}$$

distance matrix $M[i,j]\in\Theta$, finished inventory $I_f\in S$, booked inventory $I_B\in S$, market price $M_p\in S$ and cost per distance T_{cpd}

Output: A supplier $s\in S \mid \min\left[\left(I_{\mathrm{d}}\times M_p\right)+I_{\mathrm{d}}\times M(i,j)\times T_{cpd}\right]$

Given: Demand index $\mathrm{d}\in\Theta$, bucket index j with type t

Initialization:

$Cost_{(\min)} = \infty$, $Dist_{(\min)} = \infty$, $\min G_{idx} = -1$

for $k := 0$ to Θ do

if ($\Theta_k^t = \mathrm{d}_j^t$) do

if ($\Theta_k^t I_f - \Theta_k^t I_B > 0$) do

$dist = M(\Theta_k, \mathrm{d})$

$Cost_{Prod} = \Theta_k M_p \times I_\mathrm{d}$

$Cost_{Trsp} = dist \times T_{cpd} \times I_\mathrm{d}$

$Cost_{Net} = Cost_{Prod} + Cost_{Trsp}$

if($Cost_{Net} < Cost_{\min}$) do

$Cost_{\min} = Cost_{Net}$

$Dist_{(\min)} = dist$

$\min G_{idx} = k$

3.1.7. Economic Order Quantity, Reorder Point

The Economic Ordering Quantity (EOQ) is an inventory management system that establishes the quantity of a commodity such that the ordering and holding costs are minimized. The Reorder Point (ROP) of an item is a threshold at which the product needs an order placement to replenish the stock to ensure uninterrupted trade operations [25].

Input: Given a supplier $s \in S \mid \min\left[\left(I_\mathrm{d} \times M_p\right) + I_\mathrm{d} \times M(i,j) \times T_{cpd}\right]$, lead time L_t, and consumption records $C = \{c_0, c_1, \cdots, c_t\}$

Output: Updated I_{EOQ}, I_{ROP}

Initialize:

$$\min G_{idx} = \begin{cases} -1 \\ s \end{cases}$$

if ($\min G_{idx} \neq -1$) do

$$\bar{c}_\mu = \frac{\sum_{t=1}^{n} c_t}{n}$$

$$\sigma = \sqrt{\frac{\sum_{t=1}^{n}\left(c_t - \bar{c}_\mu\right)^2}{n-1}}$$

$$I_d = \bar{c}_\mu n_{days}$$

$$Cost_{Trsp} = dist \times T_{cpd} \times I_\mathrm{d}$$

$$I_{EOQ} = \sqrt{\frac{2 \times I_\mathrm{d} \times Cost_{Trsp}}{Cost_{Hold}}}$$

$$I_{ROP} = \sigma \times \sqrt{L_t} + \left(\bar{c}_\mu \times L_t\right)$$ [14] [26]

3.1.8. Vehicle Routing Problem with Multiple Pickups and Drop-Offs

The Vehicle Routing Problem with simultaneous pickup and delivery (VRPSPD) is an NP-Hard problem. Heuristic methods have proved to be more appropriate for dealing with NP-Hard problems in terms of solution quality vs. computational cost [27]. In our simulation, we have used the Genetic algorithm (GA) to solve the VRPSPD problem, with the goal of minimizing the sum of distances traveled by all vehicles of a given hub. The GA has been implemented in various combinatorial optimization problems, including vehicle routing problems [28].

Given there are $L_i = \{i \mid i \in \Theta, 0 < i < n\}$ transport hubs in a region, with each hub i containing an array of vehicles $V_k = \{k \mid k \in L, 0 < k < m\}$. Each vehicle k has a maximum carrying capacity $Q_{\max}$

Input: $O_L = \{1, 2, \cdots, n\} \in (R, I, M)$ is a list of pick and drop off orders submitted by production and consumption units with each order containing following information: pickup node $H_L^+ \in O_L$, drop off node $H_L^- \in O_L$, load $L_L \in O_L$, unit cost of load $P_L \in O_L$, freight cost of load $F_L \in O_L$

Output: Deliver orders O_L:

(a) global distance covered by all trucks $V_k \in L_i$ is minimized

(b) *or* max distance covered by any individual truck $k \in V$ is minimized

(c) *or* a combined weighted average strategy where global and individual distances covered by trucks is minimized

procedure – GA vehicle routing problem – simultaneous pickup and drop-off

begin – Step 1

Given a *depot* L_i containing an order list O_L

- Create an array of pseudo-vehicle objects $V_k^{\wedge} = \{k \mid k \in L, 0 < k < m\}$
- Create a list of populations $N_i = \{i \mid i \in O_L, 0 < i < 500\}$ each with a randomized sequence of elements $\in O_L$
- Create a list of splits $S_i = \{i \mid i \in N_i, 0 < i < m\}$ to distribute a subset of population N_i to a truck object $V_k^{\wedge}$

while (**not** terminating condition) **do – Step 2**

$i = 0$

for (*i* not greater than *N*) **do – Step 3**

a. Calculate the distance d_k traversed by each truck $\in S_i$

b. Calculate the total distance traversed $d_t = \sum_{k=1}^{m} d_k$

c. If current distance $d_t \in N_i < dist_{Min}$ **do**

$d_{Min} = dist$

$S_{best} = S_i$

d. Calculate the fitness score $d_{fitness}$ for each N_i as following:

$$d_{fitness} = \frac{1}{\left(\left[w\left(\frac{d_t}{m-1}\right)\right]^2 + \left[(1-w)(\max d_k)\right]^2\right)^{1/8} + 1}$$

where, $m \not< 2$, $w = \begin{cases} 0 \\ 0.5 \\ 1 \end{cases}$

0 → min lead time, 1 → min global distance, 0.5 → hybrid (VRP strategies)

e. Normalize the fitness scores

f. Pick 2parents with probability corresponding to relative fitness

g. Perform crossover

h. Perform mutation

i. Add a new child to the population

j. Replace the former population with the new population

end

Return to step 2

end

designate – Step 4

- Assign the S_{best} to V_k

Figure 1 represents a visual output of the pathway for a given truck between departure from hub, performing various pickups and drop-offs delivery orders, and journey back to the hub. The distance for a given population $N_i = \sum_{j=1}^{O_L} M\left(H_{Lj}^{+}, H_{Lj}^{-}\right)$.[3]

3.2. Simulation Layout

The simulation program is written in Processing® platform—a JAVA-based applet that supports object-oriented programming with additional benefit of an integrated development environment (IDE) for visual arts [29]. The simulation architectural layout is as follows:

1. Create a class (**Product)**
2. Create a class (**Bundle)** with an *ArrayList<Product>Inventory*
3. Create a class **Global** ℂ() that extends the class (**Bundle)**
4. Create a class **Production Unit** *I*( )
5. Create a class **Consumption Unit** *M*( )
6. Create a class **Transport Depots** *L*( )
7. Create a class **Customer** ℕ() with an *ArrayList<Product>Inventory*
8. Create an *ArrayList<ℂ>Chain*
9. Create an *ArrayList<I>Industries*
10. Create an *ArrayList<M>Markets*
11. Create an *ArrayList<L>Hubs*
12. Create and *ArrayList<ℕ>Customers*

[3]The simulation's essential components, Prim's Minimum Spanning Tree, Floyd Warshall Algorithm, Production Functions (cost minimization, profit maximization), demand function, and GA-vehicle routing problem, have all been independently verified, and the results are shared in a publication titled *"Simulating the impact of emissions control on economic productivity using particle systems and puff dispersion model."* https://www.youtube.com/watch?v=tXz1g64I7_k

- Declare quantities of product types *T*, number of industrial units *I*, number of markets *M*, number of customers *P*, etc.

Setup – Following steps are run at moment of program initialization.

a. Initialize a 2D grid.

b. Initialize objects for corresponding classes $\mathbb{C}()$, $I()$, $M()$, $L()$, $\mathbb{N}()$

Random function used to distribute position of Industries, Markets, and Hubs objects randomly on the 2D grid. Customers objects are distributed around Markets using a Gaussian function with a given mean and standard deviation to simulate a Central Business District (CBD)

c. Connect the *Industries, Markets, and Hub* objects using a road network by the application *Modified - Prim's Minimum Spanning Tree*

d. Create a shortest path matrix by the application of *Floyd Warshall Shortest Path* algorithm to establish route of minimum distance between any two given nodes on the network.

e. Run the *Supplier Selection* algorithm over the consumption and production objects to set up a default supplier for each commodity $t \in T$ used by an object based on minimum distance only!

f. Solve the cost minimization problem for the production units to ascertain level of labor (*L*), land (*B*) and capital (*K*) required for minimum production level *Q*

Loop – Following steps are run in loops upon conclusion of the setup

a. For each object of *ArrayList*<$\mathbb{C}$>*Chain*; check the current inventory levels of different inputs:

   - if current inventory level < reorder point, then run the Supplier Selection algorithm
   - if current inventory level < minimum inventory level, then stops production or trade

b. Construct a *vacancyIntList*() to store indexes of *ArrayList*<$\mathbb{C}$>*Chain* where current labor quantity < labor (L)*

c. Using *vacancyIntList*(); route members of *ArrayList*<$\mathbb{N}$>*Customers* to Chain objects to fill full labor requirements

d. Open markets for trade

   - Markets are only open for a specific window in a 24-hour period
   - Markets trade finished goods in exchange for money
   - Price of commodity is dynamic and based on supply and demand
   - Service time dependent on number of servers acquired
   - Level of finished inventory checked at the end of each cycle; if inventory level on a given commodity is below a threshold, *order In* variable is changed from 0 to 1
   - Customers served on First Come – First Served policy
   - M/M/c/K Queuing model for checkouts

e. Start industries for production

   - Industries only operate for a specific window in a 24-hour period
   - Industries trade money in exchange for raw and intermediate goods

used in production process

- Industries trade finished goods in exchange for money
- Minimum output is declared by programmer while max output calculated using profit maximization function
- Industries undergo capital depreciation with time
- Industries pay rent on land and wages for labor
- Level of raw material inventory checked at the end of each cycle; if inventory level on a given commodity is below a threshold, *order In* variable is changed from 0 to 1

f. Start hubs for order deliveries

- A hub can only initiate operation when all corresponding trucks and labor is present at the hub
- A hub complies a list of pick-up and drop-off orders by checking if $reqstIn = 1$ & $orderIn = 0$ on any production and consumption node
- Order information is composed of pick-up node H_L^+, drop off node H_L^-,load L_L, unit cost of load P_L and freight cost of load F_L
- Run the *Vehicle routing problem with multiple pick-ups and drop-offs.*

g. Truck deliveries

- Load each truck with a drive plan
- Sequence of deliveries is based on drive plan assigned by hub
- Vector addition, subtraction, multiplication, and magnitude functions used for simulating truck movement across the 2D plan.

4. Model Assumptions

Based on the above proposal, the following assumptions are critical in the model development:

a. The geographical area being modeled is a 2D Euclidian plane

b. Road conditions are imitated as a function of upper speed limit s_{UL}

c. Trucks speed s can vary during course of transit such that ($0 > s \le s_{UL}$)

d. Distance d between any two adjacent vertices (p,q) on the network is calculated using Pythagoras theorem. No curvature or Steiner points are permitted on the network.

e. All trucks start and end their journey at the transport hub

f. Market price of a given commodity is transient and is a function of the difference in quantities of total finished inventory I_f and total inventory booked I_B over all suppliers. The buyer pays the maximum value of either the market price or average unit cost of production. Once an order is placed in the supply chain; the price is made *fixed* irrespective of when that order is picked from seller

g. Freight cost per order is a function of the distance between pick-up and drop-off multiplied by the charge per unit distance – unit weight

h. Producers and markets place orders with transport hubs after their raw or intermediate feed levels falls below the reorder point (ROP). Economic

Order Quantity (EOQ) formula is used for calculating the size of the order placed per iteration. EOQ and ROP are dynamic in nature.

i. Producers require a minimum amount of raw and intermediate material feeds before a standard batch of finished inventory can be processed.

j. If the selling price of commodity ≤ 0, all production stops

k. Each batch of production requires a certain cycle time

l. All production plants have n identical copies. Purchase orders can only be placed with those copies where the net difference between finished inventory I_f and inventory booked $I_B > 0$

m. Order quantity moved by each truck is the minimum value of carrying capacity of truck W_{UB} or order's EOQ

n. Route planning for each truck is done at the transport depot

o. All trucks need to be present at depot before next round of deliveries can start

p. Each truck is provided with a drive plane before the start of a journey Drive plan is a set of way points the truck traverses between leaving and returning to depot

q. The buyer node credits shipment costs to transport hub upon receiving

r. No wear and tear assumed on trucks

s. Trucks take a break after the conclusion of each journey

t. No collision between trucks considered

u. Loading/unloading is instantaneous

w. All commodities are tangible goods with no expiration date.

5. Numerical Simulation

The goal of the study is the theoretical quantification of change in real-gross domestic product (r-GDP) as a direct consequence of investment in the truck-road transport system. The four (4) factors in the study are maximum speed of travel, number of trucks per hub, solution criteria for vehicle routing problem, and level of interdependence among firms. The maximum speed of travel represents the road conditions that trucks encounter while in transit, the number of trucks per hub represents the amount of freight capacity that is available in the economy, the VRT solution criteria (minimize distance, lead time, or mixed) is used to represent the effectiveness of the routing, and the interdependence criteria represents the degree of firm's integration with other firms. Given that each factor contains 3 distinct levels, Federov's exchange algorithm has been used to generate an orthogonal array that reduces the number of combination replays from 3^4 to just 9 (See appendix for detail) [30]. A summary of different speed levels, freight capacity per hub, routing efficacy, and firm interdependence for the (9) scenarios is summarized in **Table 2**.

Upon initialization the simulation generates cluster of objects *(markets, industries, resources, transport hubs)* which are uniformly distributed across the 2D region as shown in **Figure 2**. Each sector is provided with a selective range of values for each input coefficient *(land, labor, capital)* which are used in designing a production function for a given firm [31].

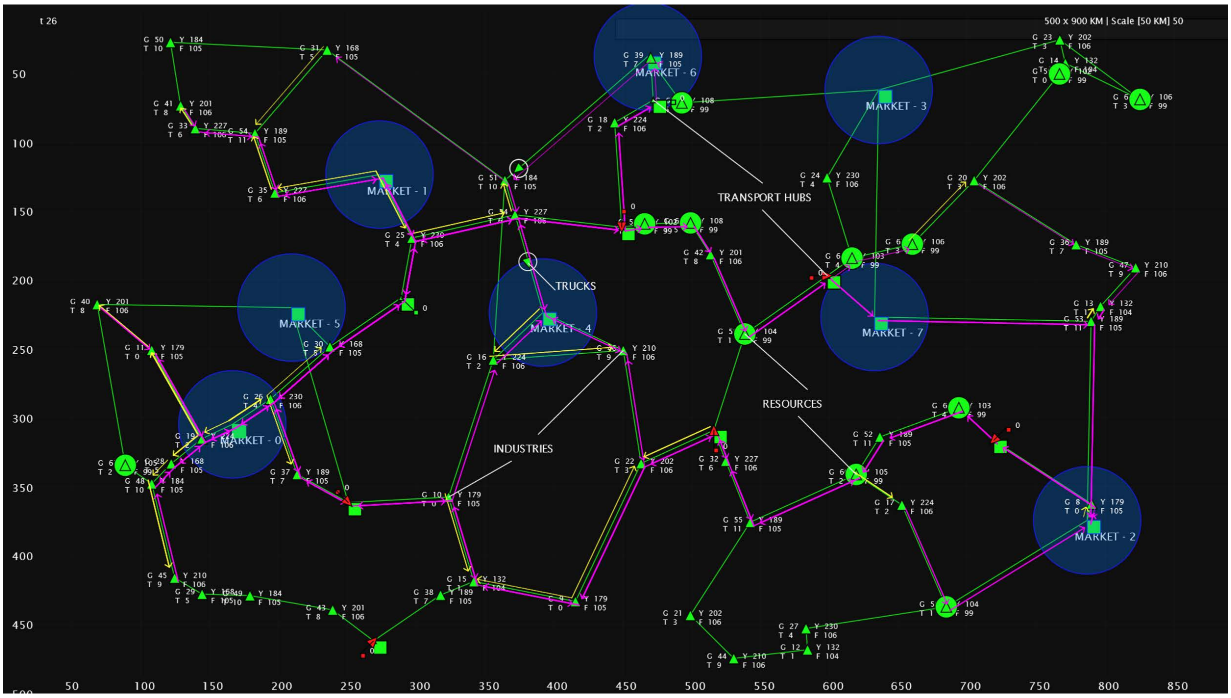
The interdependencies of firms on each other outputs is mapped upon initialization based on criteria of minimum distance as shown in **Figure 3** with linkages continuously updated during course of simulation based on criteria of finished product availability and cost of procurement. Various key parameters are kept consistent throughout all simulation scenarios, a summary of which is

Table 2. The specific level of combinations used in each of the simulation's nine scenarios.

Scenario	Max speed (KM/HR.)	# Of trucks/hub	(VRP) Criteria	Level of interdependency (M) (I) (R)
1	30	3	min:distance	(0, T, 0) (0, 2, 2) (0, 2, 0)
2	30	6	min:lead time	(0, T, 0) (0, 4, 4) (0, 4, 0)
3	30	9	mixed	(0, T, 0) (0, 6, 6) (0, 6, 0)
4	60	3	mixed	(0, T, 0) (0, 6, 6) (0, 6, 0)
5	60	6	min:lead time	(0, T, 0) (0, 2, 2) (0, 2, 0)
6	60	9	min:distance	(0, T, 0) (0, 4, 4) (0, 4, 0)
7	105	3	min:lead time	(0, T, 0) (0, 4, 4) (0, 4, 0)
8	105	6	min:distance	(0, T, 0) (0, 6, 6) (0, 6, 0)
9	105	9	mixed	(0, T, 0) (0, 2, 2) (0, 2, 0)

Table 3. Fixed parameters for all simulation scenarios.

Geographical area	950 KM × 500 KM
Commodity types	$T = \{t \in \mathbb{N} \mid 0 > t \le 12\}$
No. of industries	4 replicates of industry $p \in I$ for each type $t \in T$ (48 industrial units)
No. of markets	$M = \{m \in \mathbb{N} \mid 0 > m \le 8\}$
Resource types	$H = \{h \in \mathbb{N} \mid 0 > h \le 8\}$
No. of mining firms	2 replicates of resource $r \in R$ for each type $h \in H$ (12 extraction units)
No. of transport hubs	$L = \{l \in \mathbb{N} \mid 0 > l \le 8\}$
Length of road network	9411 KM
Production firms operating period	8 hours/day
Markets operating period	16 hours/day
Depreciation rate of capital	0.0833%/day
Market-service rate/station	1 second /order



Legend: Traversal - Unloaded (→), Traversal - Loaded (→)

Figure 1. Vehicle routing problem with multiple pickups-drop offs. In the above display, the hub (0) articulated drive plan shows the different waypoints the truck (0) must traverse to perform successive pick-up and drop-off orders. The pathway between any pick-up and drop-off order is determined using the Floyd Warshall shortest path matrix.

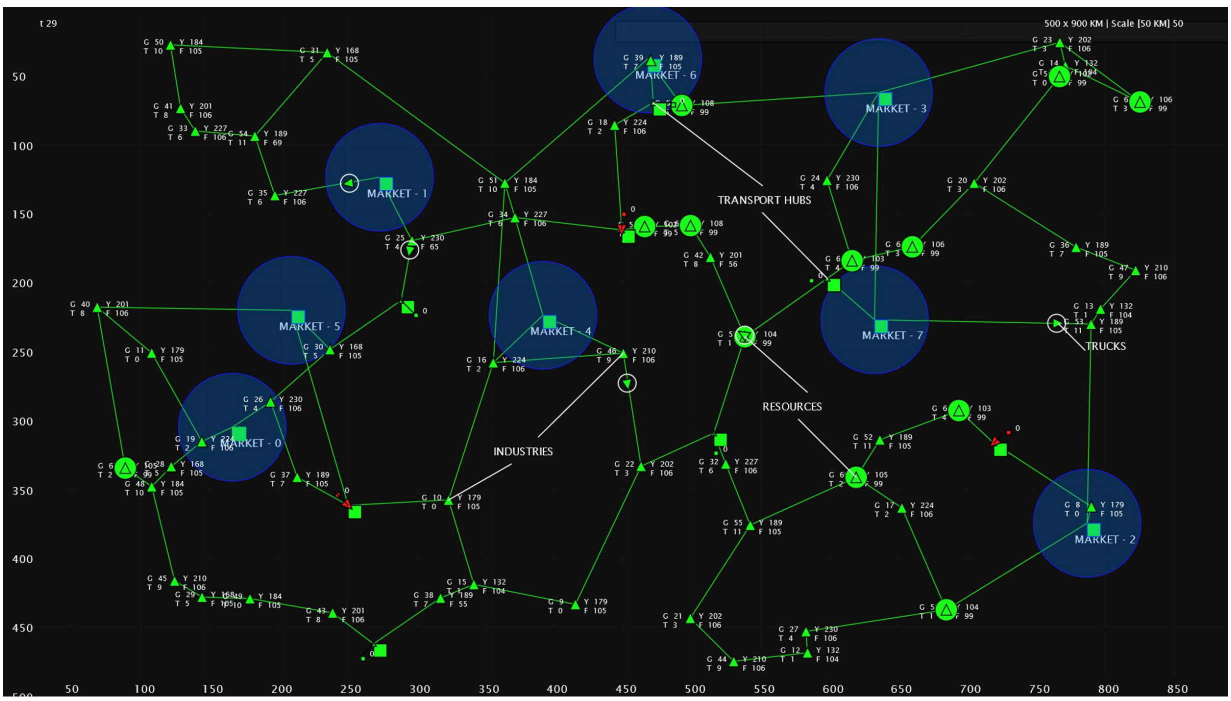
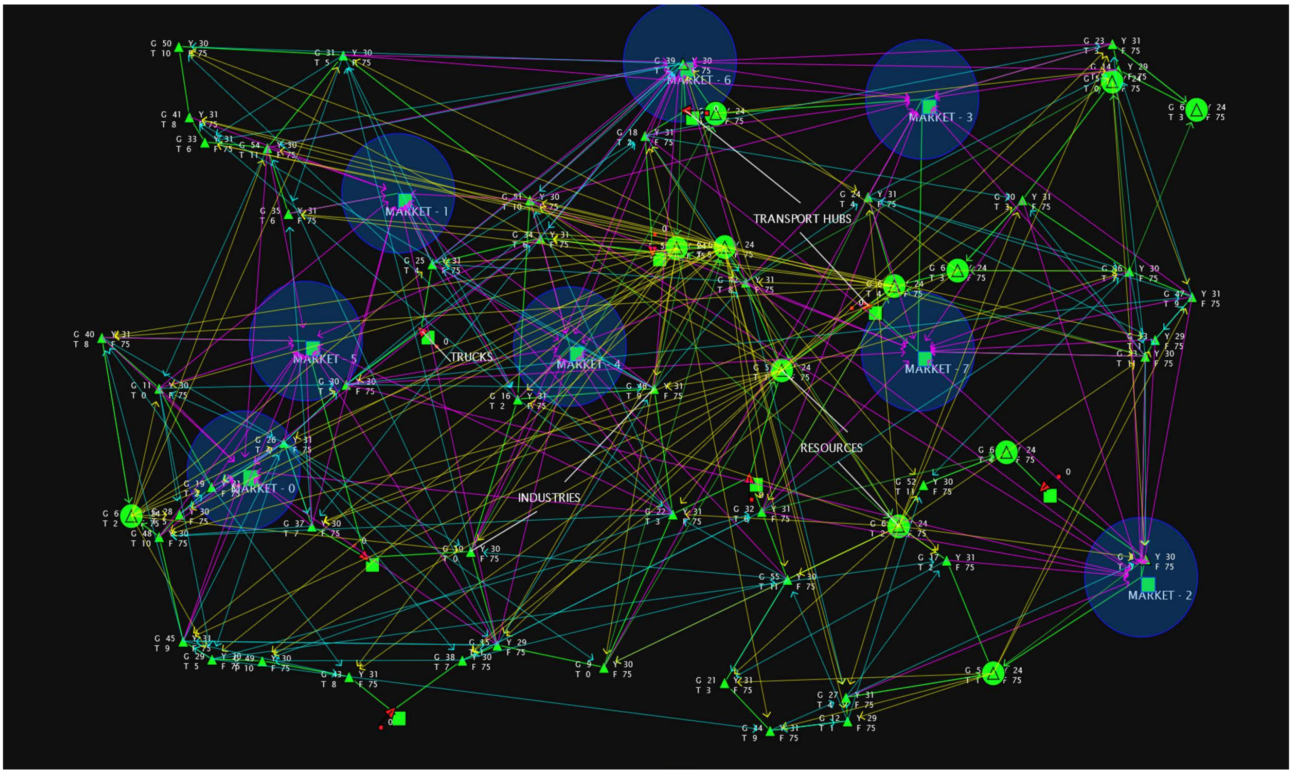


Figure 2. A 2D spatial output of the economic assessment platform. The display shows random distribution of various resources, industries, transport hubs and markets over a 900 KM × 500 KM area. The road network is conceived by the application of Prim's Minimum Spanning Tree (MST) algorithm, with extra edges added to create close loops. Trucks (circled white) use the road network to channel goods between pickup and drop-off points. The total length of the road network is 6127 KM.



Legend: Industries to markets (→), Industries to industries (→), Industries to resources (→), Resources to industries (→)

Figure 3. The interdependence of firms on each other's output. In above display, the level of interdependence (M, I, R) for industries is (0, 2, 2), for resources (0, 2, 0) and for markets is (0, n, 0). (M, I, R) indicates number of corresponding markets, industries and resources inputs a given production or consumption node requires to operate.

discussed in **Table 3**. Each scenario in the simulation is ran for the period of 3600 seconds with each day in the simulation composed of 24 seconds. Values of various macroeconomic indicators that are recorded at the end of each day include quantity of finished units produced to date, quantity of finished units consumed to date, volume of missed sales, gross GDP, nominal GDP, inflation index, combined cost of transport to date, value of finished products moved to date, average lead time of delivery, and interest rate. Summary of findings for various macroeconomic indicators are as following:

5.1. Real-Gross Domestic Product (r-GDP)

The evolution of r-GDP under nine different scenarios is summarized in **Figure 4**. r-GDP rises sharply during the initial phases of all scenarios but with passage of time deviations start to develop among various scenarios. At the 129th day of the simulation the ranking of real-GDP from the highest (left) to lowest (right) value for 9 different scenarios is as following:

Scenario	5	9	1	2	7	6	8	3	4
Real-GDP	6.472	6.467	4.828	2.905	2.618	1.910	0.549	0.108	−0.009

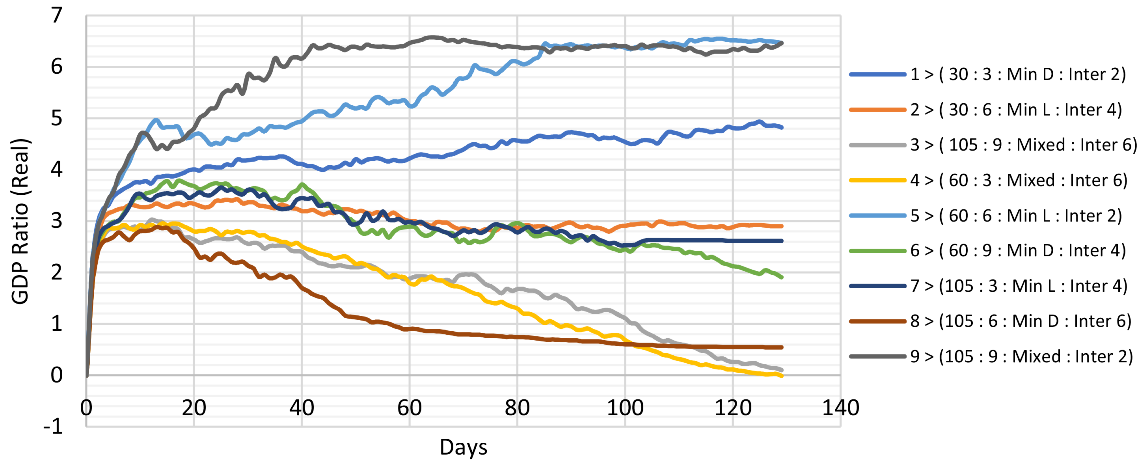


Figure 4. Real-Gross GDP ratio under 9 different scenarios. The legend on the right-hand side displays various combinations of speed (km/Hr), capacity (number of trucks per hub), strategy of vehicle routing problem, and interdependence parameter respectively for 9 scenarios.

Analysis of Variance Table

Response: rGDP

	DF	Sum Sq	Mean Sq	F Value	Pr (>F)	
Speed	1	0.558	0.558	1.0667	0.377649	
NTrks	1	0.183	0.183	0.3501	0.595705	
VRPStr	2	7.144	3.572	6.83	0.076406	.
IntrDep	1	42.584	42.584	81.4359	0.002873	**
Residuals	3	1.569	0.523			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1''1

These ANOVA results indicate firm's interdependency plays the most significant role on the growth of real-GDP growth, followed by a strategy implemented in solving the vehicle routing problem (VRP), whereas the speed and capacity (number of trucks) had no effect. This means increasing the speed of deliveries or having a higher transport capacity may not necessarily increase real-gross domestic product in an environment where the level of interdependency among firms is extreme and levels of storage reserves is constrained. Initially, scenarios with high levels of interdependencies produced GDP growth matching the ones that did not, however, with passage of time firms start running out of input feeds and the level of productivity started to depreciate.

5.2. Nominal-Gross Domestic product (n-GDP)

The evolution of n-GDP under nine different scenarios is summarized in Figure 5. At the 129th day of the simulation, the ranking of n-GDP from the highest (left) to lowest (right) value for 9 different scenarios is as follows:

Scenario	1	5	6	2	4	9	8	3	7
Nominal GDP	23.311	13.923	10.209	9.6244	7.297	6.756	6.737	6.285	5.563

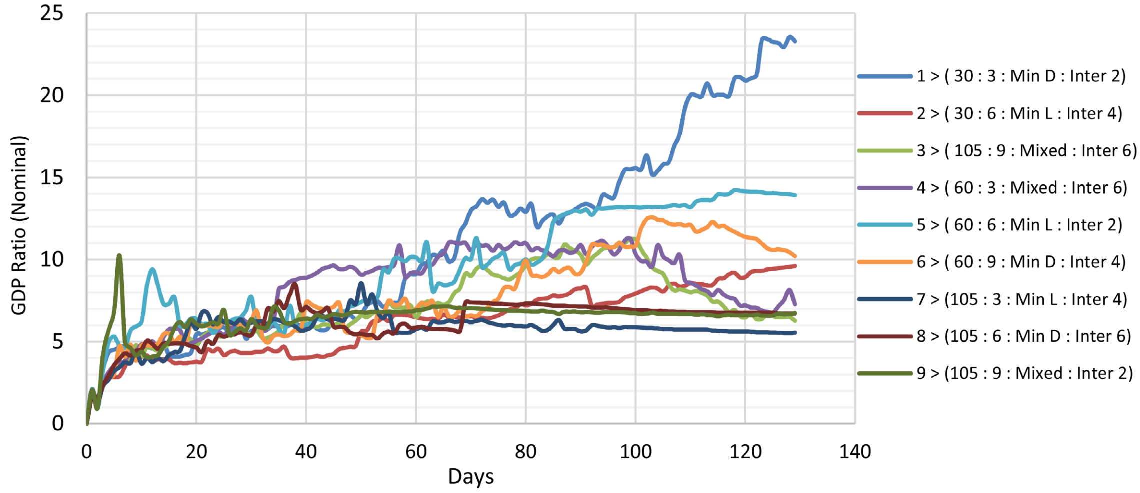


Figure 5. Nominal-Gross GDP ratio under 9 different scenarios.

Analysis of Variance Table

Response: nGDP

	DF	Sum Sq	Mean Sq	F Value	Pr (>F)	
Speed	1	68.352	68.352	31.827	0.011021	*
NTrks	1	27.825	27.825	12.957	0.036775	*
VRPStr	2	58.570	29.285	13.636	0.031197	*
IntrDep	1	88.891	88.891	41.391	0.007613	**
Residuals	3	6.443	2.148			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1'' 1

These ANOVA results indicate speed, transport capacity (number of trucks), solution strategy implemented for vehicle routing problem and firm's interdependency all play a significant role in nominal-GDP growth. The most significant level is recorded for the interdepended parameter, followed by speed of travel, VRP strategy, and transport capacity respectively. Compared to r-GDP, the n-GDP values are affected both by number of units produced as well as unit prices. In scenarios where the level of productivity has fallen the unit prices have inflated to balance supply and demand.

5.3. Inflation

The inflation values under nine different scenarios are summarized in Figure 6. It can be observed that the inflation rises initially under all scenarios except scenarios 1 and 2 start to level off. At the 129th day of the simulation, the ranking of inflation from the lowest (left) to highest (right) value for 9 different scenarios is as follows:

Scenario	9	7	8	2	5	3	6	4	1
Inflation	2.265	3.163	3.641	3.772	4.060	4.601	4.997	5.694	7.366

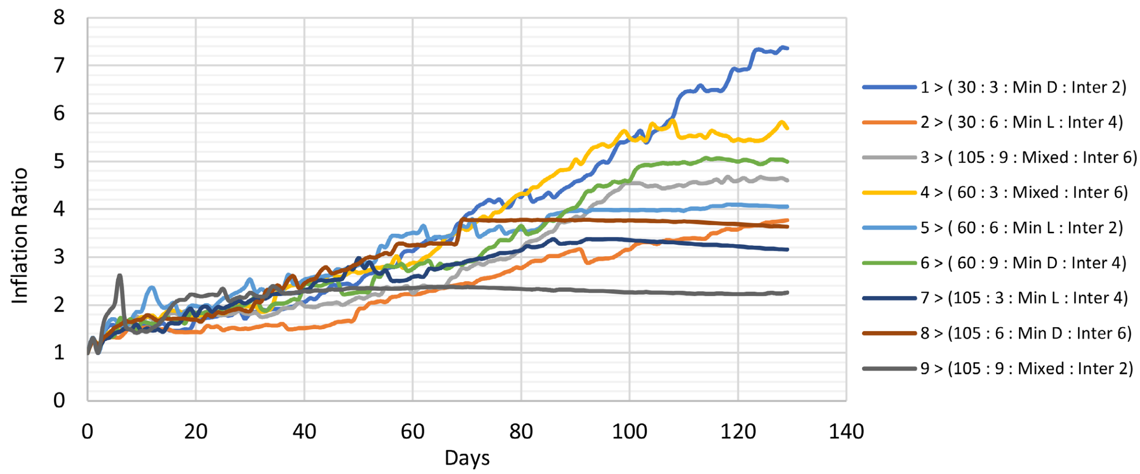


Figure 6. Inflation ratio under 9 different scenarios.

Analysis of Variance Table						
Response: Inflation						
	DF	Sum Sq	Mean Sq	F Value	Pr (>F)	
Speed	1	8.0200	8.0200	23.4315	0.01682	*
NTrks	1	3.1683	3.1683	9.2566	0.05576	.
VRPStr	2	5.6778	2.8389	8.2943	0.05993	.
IntrDep	1	0.1498	0.1498	0.4377	0.55550	
Residuals	3	1.0268	0.3423			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1'' 1						

These ANOVA results indicate that speed is the most significant factor in inflation, with logistical capacity and VRP-strategy having little effect and interdependency having no effect. The inflation is higher for scenarios where the speed of travel is restricted.

5.4. Interest Ratio

The values of interest rate under nine different scenarios are summarized in **Figure 7**. It can be observed that the interest rates fall immediately at the start of the simulation and then rise sharply before starting to stabilize except in case of scenarios 1 and 2. At the 129th day of the simulation the ranking of interest rate from the lowest (left) to highest (right) value for 9 different scenarios is as follows:

Scenario	8	6	7	9	3	4	5	2	1
Interest rate	1.6529	1.942	1.9964	2.0056	2.2288	2.3912	2.4015	3.7725	5.4585

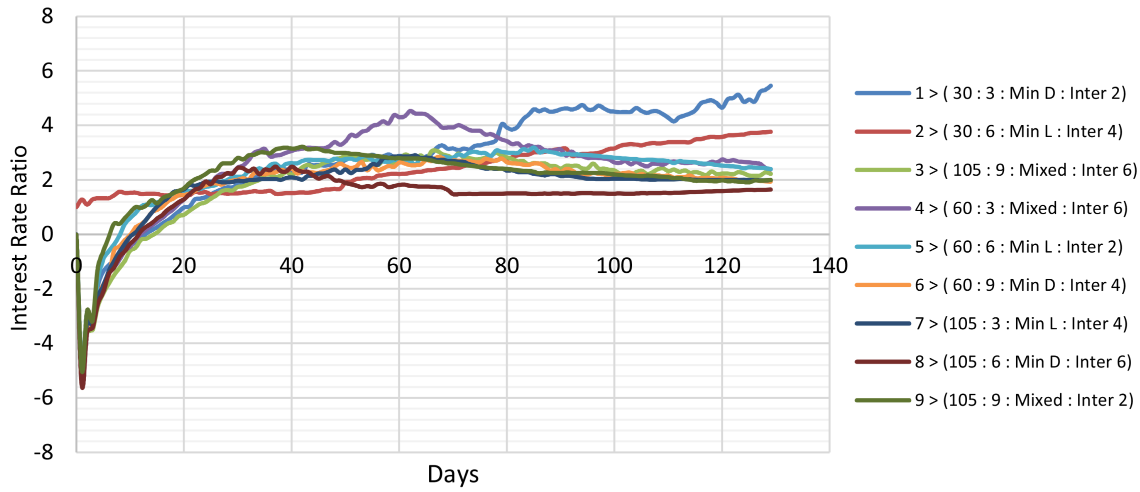


Figure 7. Interest ratio under 9 different scenarios.

Analysis of Variance Table

Response: Interest

	DF	Sum Sq	Mean Sq	F Value	Pr (>F)	
Speed	1	5.7805	5.7805	11.0757	0.04479	*
NTrks	1	1.8432	1.8432	3.5316	0.15681	
VRPStr	2	0.7441	0.3720	0.7128	0.55810	
IntrDep	1	2.4112	2.4112	4.6199	0.12078	
Residuals	3	1.5657	0.5219			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1'' 1

These ANOVA results indicate that speed is the most significant factor in interest rate, with logistical capacity, VRP strategy, and interdependency having no effect. The interest rate is higher for scenarios where the speed of travel is restricted.

5.5. Delivery Time

The evolution of delivery times for nine different scenarios is summarized in Figure 8. The ranking of average delivery times from the lowest (left) to highest (right) value for 9 different scenarios is as follows:

Scenario	9	8	5	7	6	3	4	1	2
Delivery Time	1.3153	2.2928	4.7215	5.957	9.822	13.46	13.897	18.41	20.82

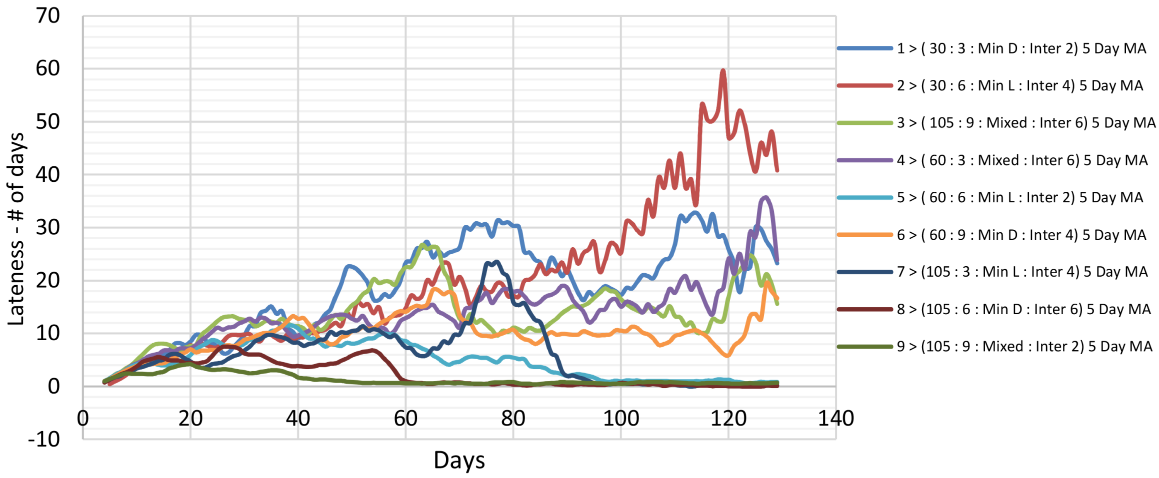


Figure 8. 5-Day Moving average delivery times under 9 different scenarios.

Analysis of Variance Table

Response: Delivery time

	DF	Sum Sq	Mean Sq	F Value	Pr (>F)	
Speed	1	300.952	300.952	15.7001	0.02891	*
NTrks	1	31.143	31.143	1.6247	0.29220	
VRPStr	2	0.602	0.301	0.0157	0.98450	
IntrDep	1	3.949	3.949	0.2060	0.68074	
Residuals	3	57.506	19.169			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

These ANOVA results indicate that speed is the most significant factor in delivery time, with logistical capacity, VRP strategy, and interdependency having no effect. The delivery times are higher for scenarios where the speed of travel is restricted.

5.6. Consumption versus Production Ratio

The consumption versus production ratio (units) for nine different scenarios is summarized in Figure 9. At the 129th day of the simulation, the ranking of delivery times from the highest (left) to lowest (right) value for 9 different scenarios is as follows:

Scenario	4	3	8	6	7	2	9	5	1
Consumption Production Ratio	1.123	1.112	1.079	0.923	0.915	0.843	0.731	0.709	0.672

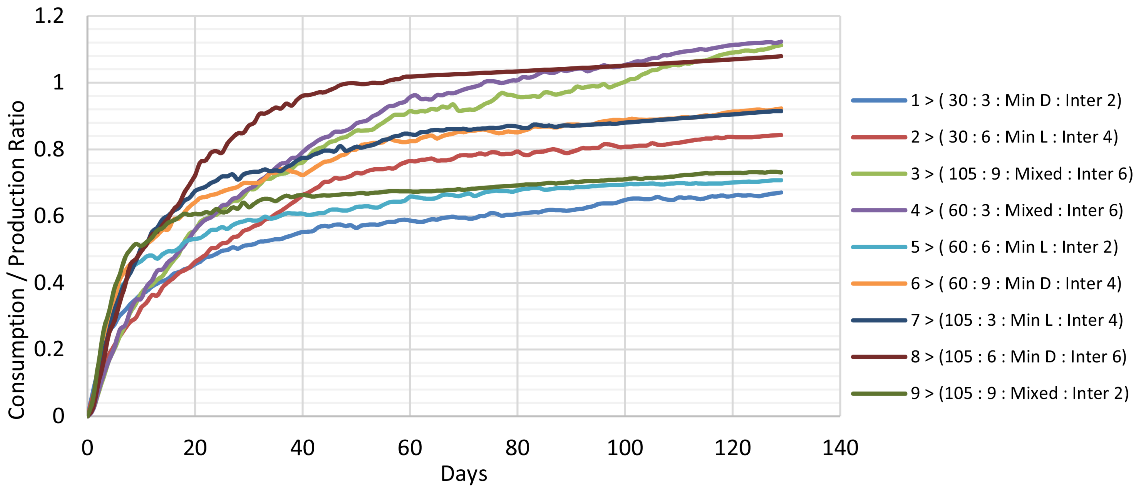


Figure 9. Consumption to Production ratio observed under 9 different scenarios.

Analysis of Variance Table

Response: Cons vs Prdx Ratio

	DF	Sum Sq	Mean Sq	F Value	Pr (>F)	
Speed	1	0.001272	0.001272	1.1276	0.3662037	
NTrks	1	0.000513	0.000513	0.4552	0.5482304	
VRPStr	2	0.043777	0.021888	19.4066	0.192181	*
IntrDep	1	0.199193	0.199193	176.6076	0.0009208	***
Residuals	3	0.003384	0.001128			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1'' 1

These ANOVA results indicate firm's interdependency and VRP-strategy plays the most significant role on the consumption vs production ratio, whereas the speed and transport capacity have no effect. This means increasing the speed of deliveries or having a higher transport capacity may not increase consumption vs production ratio in an environment where the level of interdependency among firms is extreme. Figure 9 indicates that having a higher interdependency factor among firms promotes higher consumption which is contradictory to r-GDP in Figure 4. Basically, in scenarios of high interdependencies most consumption occurs in the initial stages of the simulation until all finished product reserves have been exhausted.

5.7. Freight Contribution to the Total Value of the Product

The freight contribution to total value of product ratio ($) for nine different scenarios is summarized in Figure 10. At the 129th day of the simulation, the ranking of freight contribution from the lowest (left) to highest (right) value for 9 different scenarios is as follows:

Scenario	6	8	3	5	9	4	7	2	1
Freight Contribution Ratio	0.2564	0.2642	0.3061	0.324	0.3535	0.388	0.388	0.573	0.704

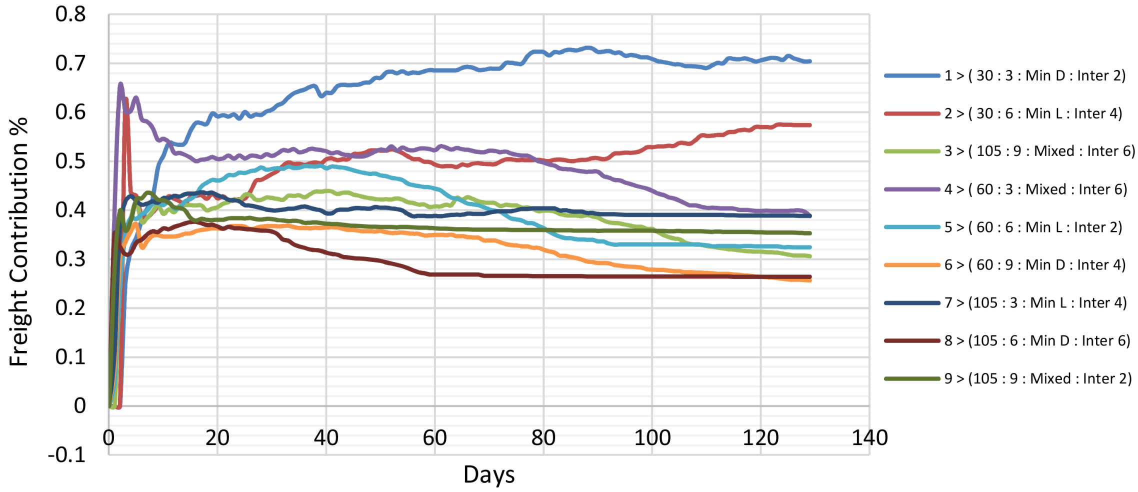


Figure 10. Freight contribution to total value of product under 9 different scenarios.

Analysis of Variance Table

Response: Freight Contribution

	DF	Sum Sq	Mean Sq	F Value	Pr (>F)
Speed	1	0.047039	0.047039	3.0607	0.1785
NTrks	1	0.053336	0.053336	3.4705	0.1594
VRPStr	2	0.001212	0.000606	0.0394	0.9618
IntrDep	1	0.031202	0.031202	2.0303	0.2494
Residuals	3	0.015368	0.015368		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

These ANOVA results indicate that speed, transport capacity, VRP-strategy and interdependency among firms have no significant effects on freight contribution. The primary reason could be that the cost of manufacturing and inflation caused by the differences in supply and demand far exceed the costs incurred by freight[4].

5.8. Principal Component Analysis

Principal component analysis (PCA) is a dimension reduction technique for deriving a low-dimensional set of features from a large set of variables. When the PCA technique is applied to the results of the simulation, the scatter plot of Figure 11 is obtained.

[4]Freight charge per unit distance – weight equation declared in the appendix.

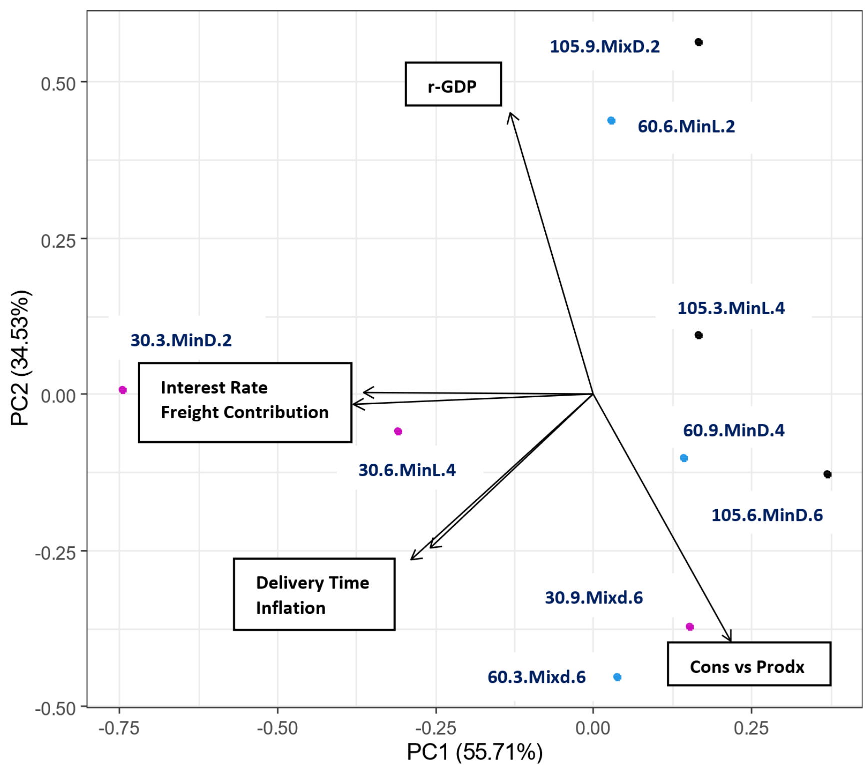


Figure 11. Principal component analysis on simulation results.

The first principal component direction (PC1) is along observations that vary the most. The second principal component (PC2) is the linear combination of the variables that are uncorrelated with the (PC1) and the largest variance subject to a constraint [32].

Figure 11 PCA Interpretation

The PC1 places the most weight on the interest rate and freight contribution, while with much less weight on r-GDP and consumption versus production ratio. The delivery time and inflation rate are much less equally weighted along both PC1 and PC2. When we compare the positions of our loadings (r-GDP, interest rate, inflation, etc.) against the scores assigned to various scenarios by the first two principal components, we can deduce that speed is a primary factor in PC1. At the same time, the interdependency parameter is a significant factor in PC2. The PC1 and PC2 can explain 90.23% of the total variance in the simulation results.

The loading vectors in **Figure 11** suggest that economies with a minimal level of interdependencies experience a high level of real-GDP growth, while those with a high level of interdependencies experience a high level of consumption vs. production ratio. Economies where the speed of freight travel is sluggish experience a high-interest rate, and freight contribution to the total value of finished goods is relatively higher. Economies with a slower speed of travel and a higher interdependency factor experience longer delivery times and a high inflation rate.

6. Conclusions

Many impoverished regions around the globe lack access to reliable transport systems irrespective of being abundant in natural resources. Firms require a timely transfer of intermediate goods to guarantee an uninterpreted production flow. Given the firms' high interdependencies on each other's production, any disruption in the flow of input feeds can have damaging consequences for the overall economy.

This study examines the reliability of a truck-road transport system and its effect on various macroeconomic indicators. The effect of speed travel, transport capacity, the routing efficiency on the growth rate of productivity, rate of inflation, freight contribution to the total value of the product, average delivery times, and consumption-to-production ratio under various degrees of interdependencies between firms are examined. Details of the methodology, including formulation and integration of various concepts from operations research, object-oriented programming, microeconomics, and graph theory for a simulation platform, are discussed in the earlier sections.

The simulated analysis was tested on an economy with 12 different industries, 6 different resources, 8 market centers, and 8 transport hubs, each with several competitors[5]. The variables in the economy included 4 factors: speed, capacity, VRP strategy, and interdependency factor, each with 3 respective levels (30, 60, 105), (3, 6, 9), (Min distance, Min lead time, mixed), (2, 4, 6). The fractional factorial design is applied to reduce the number of simulation reruns from 81 (3^4) to 9, with each simulation run for 3600 seconds.

The simulation results indicate that of the four (4) factors, interdependency followed by speed has the most significant effect on the gross domestic product, inflation, average delivery time, and freight contribution to the total product value. High GDP growth is experienced when the interdependency factors among firms are kept minimum with a high speed of freight delivery. An extreme form of mutuality among firms is counterproductive since a few firms' productivity disruptions can have a cascading effect on the whole economy. Production activity falls rapidly due to gridlock formation, where industries cannot perform value-added operations due to the absence of inputs from other industries. The importance of freight speed, transport capacity and routing efficiency is secondary in an economy where production firms are highly interdependent with the non-existence of any reserves. Impoverished regions can experience high growth in productivity by setting industries where the dependency on other industries' input is minimally followed by investment in road networks.

The study can be expanded further by embedding other modes of transportation, such as railroads and waterways, and quantifying the degree of improvements of these yields toward economic growth. Other research venues can be the

[5]Multiple copies of a given object (industry, resource) is introduced in the simulation with minor variation production function. All copies of a given object produce same type of output but compete for market share.

capital recovery analysis of investments in the transport networks and the existing platform as a location analysis tool for a given facility system.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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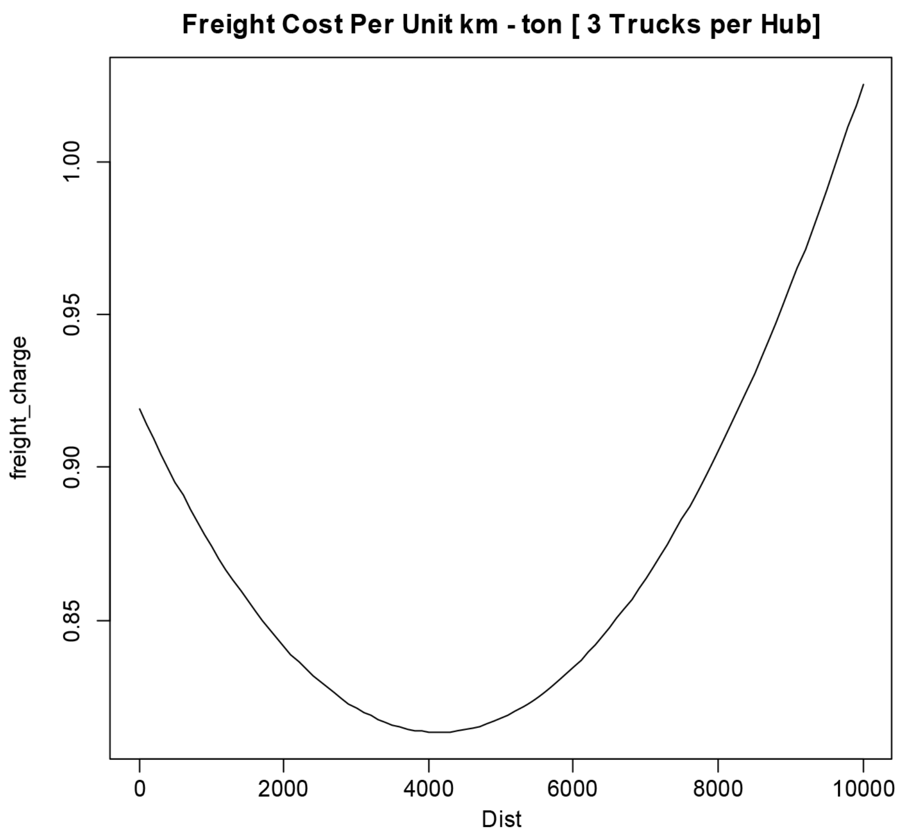
Appendix

Fractional factorial design

```
require ("AlgDesign")
require ("DoE.base")
require ("FrF2")

cand <- oa.design(nlevels = c(3, 3, 3, 3), randomize = FALSE, seed = 2013)
optim<- optFederov( ~ A + B + C + D, cand, nRepeats = 12, nTrials = 9, criterion = "D", aug =
FALSE)
```

Result: $D - 0.3766103, $A - 2.777778, $Ge – 1, $Dea – 1



Freight charge per unit distance – weight

$$t_{Demand} = d/(s \times m)$$

$$\Delta = t_{70} - t_{Demand}$$

$$F_{charge} = (0.0002 \cdot \Delta^2) - (0.0188 \cdot \Delta) + 1.2552$$

where:

t_{Drive} drive time booked

t_{70} normal hours of operation (per week)

d	distance
s	speed
m	number of trucks for freight delivery
f_{charge}	freight charge (km-per ton)

Principal Component Analysis (PCA)

```
Comb   <- c("30.3.MinD.2", "30.6.MinL.4", "30.9.Mixd.6",
      "60.3.Mixd.6", "60.6.MinL.2", "60.9.MinD.4",
    "105.3.MinL.4", "105.6.MinD.6", "105.9.Mixd.2")
rGDP   <- c(4.828, 2.905, 0.108, -0.009, 6.472, 1.910, 2.618, 0.549, 6.467)
infl   <- c(7.366, 3.772, 4.601,   5.694, 4.060, 4.997, 3.163, 3.641, 2.265)
intr   <- c(5.459, 3.773, 2.223,   2.391, 2.402, 1.943, 1.996, 1.653, 2.001)
delT   <- c(18.414, 20.825, 13.461, 13.897, 4.7215, 9.822, 5.957, 2.2928, 1.3153)
CvsP   <- c(0.672, 0.843, 1.112, 1.1235, 0.709, 0.923, 0.915, 1.0795, 0.731)
FrCo   <- c(0.7046, 0.5739, 0.3061, 0.3885, 0.3242, 0.2564, 0.3886, 0.2642, 0.3535)

Sim    <- data.frame(rGDP, infl, intr, delT, CvsP, FrCo)
rownames(Sim) <- Comb
pr.out = prcomp(Sim, scale = TRUE)
names(pr.out)

## mean
pr.out$center
## sd
pr.out$scale
## principal component loading
pr.out$rotation
biplot(pr.out, scale = 0)

pr.out$rotation = -pr.out$rotation
pr.out$x = - pr.out$x
biplot(pr.out, scale = 0)

pr.out$sdev
pr.var = pr.out$sdev^2
pve = pr.var/sum(pr.var)
pve

plot(pve, xlab = "Principal Component", ylab = "Proportion of Variance Explained", ylim = c(0,1), 
type = 'b')
plot(cumsum(pve), xlab = "Principal Component", ylab = "Cumulative Proportion of Variance Ex-
plained", ylim = c(0,1), type = 'b')

library(ggplot2)
library(ggfortify)
```

```
d <- autoplot(pr.out, data=Sim, colour=Comb, loadings=TRUE, loadings.colour = "black", scale =
1)+ _text(alpha=.4, size=3, aes(label=rownames(Sim)))+
scale_colour_manual(values=c("forestgreen","red","blue")) +
scale_fill_manual(values=c("forestgreen","red","blue")) +
scale_shape_manual(values=c(25,22,23))+theme_bw()

d$layers[[2]]$aes_params$size<- 0.5
d$layers[[2]]$geom_params$arrow$length<- unit(6, units = "points")
d
```