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Abstract: The conventional intermodal freight transportation system lacks the needed flexibility, efficiency and effectiveness among other things. The search for more sustainable system for maritime-hinterland transportation has culminated in the development of the synchromodality concept. In this study, mathematical model is formulated and used to experiment the feasibility and applicability of the concept of synchromodality in Ghana. Data for the numerical analysis for the given corridor is obtained from online sources and through the direct interview of experts in the field. Coupled with this, expert judgment of the researchers is also used. The results of the optimisation were plotted in a graph using OriginPro 9.0, 32-Bit Software. From the study results, the synchromodal service design yielded a difference of about 22% cost savings compared with the unimodal service due to the usage of fewer of trucks. The waiting penalty at the terminal of origin is also considerably reduced. When compared with the intermodal service, the synchromodal service offered a cost savings of about 8%. The results of this research show that the innovative concept has the potentials of ensuring sustainability, flexibility and cost reduction among other things, in freight transportation sector. The sustainability is obtained through better modal split and parallel use of modes for maritime-hinterland freight transportation. Furthermore, the study reveals that synchromodality has the potentials of increasing transport service utilisation. The benefits of

ABOUT THE AUTHORS

Aaron Agbenyegah Agbo is a Senior Lecturer at Accra Institute of Technology (AIT), Ghana, and currently a Logistics and Transportation Consultant in the Ghana Prisons Service. His research interests include Sustainable Transportation Management, Logistics Management, Freight Transportation Management, Procurement and Supply Chain Management, Road Transport and Fleet Vehicle Management. The study reported on in this article is the second part of series of studies being currently undertaken in Ghana.

Yanwei Zhang is an Associate Professor in the School of Logistics Engineering, Wuhan University of Technology. Her research interests are Ports Logistics, Planning of Logistics Systems, Optimisation and Supply Chain Management.

PUBLIC INTEREST STATEMENT

The recent growth in the global supply chain has resulted in the long travel of goods from producers to consumers with its associated cost implications. The long distance of moving goods has culminated in higher consumption of fuel leading to increasing greenhouse gas (GHG) emissions and atmospheric pollution. These negative effects are brought about due to over-reliance on road freight transportation. This is evident in freight transportation from ports to hinterlands. Finding a sustainable system for maritime-hinterland freight transportation has become a concern to all in the field of logistics and transportation. Our previous study presented a feasibility study carried out for the introduction of the concept of synchromodal freight transportation system. In this study, a mathematical model is used to experiment the applicability of the concept. This paper motivates, assists and inspires all researchers interested in sustainable freight transportation system through integrated transport modes.
environmental sustainability are achieved through less usage of trucks resulting in a reduction in environmental pollution, road congestion, noise, etc.

Subjects: Environment & Agriculture; Environmental Studies & Management; Mathematics & Statistics; Engineering & Technology; Development Studies, Environment, Social Work, Urban Studies; Urban Studies; Development Studies; Economics, Finance, Business & Industry; Geography

Keywords: sustainable freight transportation systems; intermodal transportation system; synchromodality; logistics; supply chain management

1. Introduction

The current boost in the world economy is partly due to developments and innovations in the transportation sector (Agbo, Li, Atombo, Lodewijks, & Zheng, 2017; Agbo, Li, Zheng, Zhang, & Atombo, 2017; Jeon, Christy, Adjo, & Vanegas, 2006). Transportation has been one of the major determining factors in the choice of location for industries and human settlements. Transportation is thus linked with the very well-being of humans, and the economic development of a nation. Transportation helps in bridging the gaps between suppliers, manufacturers, distributors, retailers, and consumers in the supply network (Agbo, Li, Atombo et al., 2017). It ensures the movement of goods and materials from one location to another in the physical distribution process. However, with all the positive benefits derived from transportation, there are also negative impacts arising from the development and use of transportation hence the need for careful planning to mitigate the challenges emanating from the transportation sector (Agbo, Li, Zheng, et al., 2017; Bowen & Leinbach, 2006; Lu & Li, 2010).

The traditional approach to transportation planning and its associated activities is mainly focused on cost reduction and increasing of profitability (Agbo, Li, Atombo et al., 2017; Hwang & Ouyang, 2015). Much consideration is given to internal costs of transportation such as drivers’ remunerations, fuel costs, maintenance, etc. (Agbo, Li, Atombo et al., 2017; Gobetto, 2014). This approach is very particular in the freight transportation industry. In recent times, government concerns and legislations about environmental pollution and carbon emissions from industries and organizational activities is calling for new and an innovative approach to modelling and optimizing freight transportation planning and activities. This demand from governments has woken up the interest in all organizations to start realizing and focusing maximum attention on the importance and necessity of dealing with the environmental and social effects such as air pollution, noise, congestions, etc. as a result of transportation activities (Boschian, Paganelli, & Pondrelli, 2013; Guo & Aultman-Hall, 2014).

Freight transportation has been identified as a major contributor to the negative impacts arising from all logistics and industrial activities (Agbo, Li, Atombo et al., 2017; Agbo, Li, Zheng et al., 2017; Pauli, 2016). In view of this, researchers and individual organizations are putting up efforts in finding solutions to the problem. The introduction of multimodal, intermodal and co-modal freight transportation network systems was thought to be means by which the high cost and environmental pollutants from the freight transport sector could be reduced. The efforts can provide partial solutions to the undesirable consequences from the freight transportation sector. However, there exists more to be done, especially regarding reducing the pollutants from the road freight transport sector and this is a major concern to all governments globally. This has consequently led to national and international regulations and policies regarding industrial activities and their pollutions levels (Hwang & Ouyang, 2014; McKinnon, 2016; Pauli, 2016; Psaraftis, 2016).

Industries and researchers are finding better alternatives and strategies to avoid sanctions with regards to environmental and other sustainability issues (Agbo, Li, Atombo et al., 2017). In this study, the concept of synchromodality is introduced as the most current innovative concept in freight transportation in ensuring sustainability in the freight transport industry (Bloemhof, Van der Laan, & Beijer, 2011; Lucassen & Dogger, 2012; Van den Berg & De Langen, 2015).
Synchromodal transportation is an outcome of the many such research efforts (Agbo, Li, Atombo et al., 2017; Bloemhof et al., 2011; Rohács & Simongati, 2007). Synchromodality is thought to be the present solution to the many environmental and economic problems arising from the freight transportation sector. Synchromodality is the optimally flexible and sustainable deployment of different modes of transport in a network under the direction of a logistics service provider so that the customer (shipper or forwarder) is offered an integrated solution for its transport (Platform Synchromodaliteit, 2012).

Synchromodality uses an integrated network of various transport modes available in parallel to provide flexible transport solution with great optimality (Zhang & Pei, 2016). Since there are different players within the synchromodal system, there is the need for the corporation coordination of information for real-time management of the system. Integrated network design, real-time switching, are key to the realization of synchromodality. To achieve real-time switching the is the need for the collection and utilization of real-time data such as information about infrastructure, transport modes, transport services and prices, container position in transit, weather conditions, etc. this information are needed in real-time. In synchromodal solutions, the main essential issue is about the modal booking. The decision about the modalities is left to the logistics service provider. Seamless switch between modes is an important mechanism for synchromodal solutions. This applies to transportation scheduling as for when dealing with unexpected situations planned before or during the execution of the transport (Boschian & Paganelli, 2016; Lucassen & Dogger, 2012; Tavasszy, Behdani, & Konings, 2015).

The door-to-door logistics supply chain consists of several modalities and the integration of the various modes of transport in the multimodal and intermodal freight transport systems have received the attention of many researchers over the years with the main focus on the vertical integration of logistics services as part of the transportation supply chain (Rossi, 2012). Vertical integration concept has more to do with the concept of Dry Ports. This concept demands much integration between the operations of maritime terminals and inland terminals. The horizontal integration of logistics supply chain is as well necessary to obtain an efficient system. In the synchromodal transportation system, the main aim is the horizontal system integration. In this concept, coherent transport product is achieved through the proactive integration of transport services among the various modalities in the synchromodal system (Commission, OECD/Eurostat/United Nations Economic, 2010; Dekker, Bloemhof, & Mallidis, 2012; Energy, European Commission. Directorate-General for, 2006; Rossi, 2012).

1.1. Sustainability in freight transportation
The concept and principles of sustainability became a pursuit for many policy makers, professionals and scholars in the development of urban and metropolitan planning after the Brundtland Commission report in 1987 (Brundtland et al., 1987). The concept since then has proven to be an enduring and compelling one, and attempts have been made to incorporate it into all technological, social and economic endeavours such as manufacturing, construction, etc. The policy application has also been incorporated into the management of supply and logistics chain in recent times due to government regulations, customer demands, and benefits derived from the concept (Ahi & Searcy, 2015; Boukherroub, Ruiz, Guinet, & Fondrèvelle, 2015; Brandenburg, Govindan, Sarkis, & Seuring, 2014).

Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet theirs.” (Brundtland et al., 1987; Carter & Rogers, 2008). The concept, as incorporated in supply chain management, has been defined by Rogers as “sustainable supply chain management (SSCM) is the strategic, transparent integration and achievement of an organization’s social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of an individual company and its supply chain” (The Sustainable Supply Chain Project, 2013).
Three broad concepts are formulated out of the definition of sustainability, and these are environmental, social and economic sustainability. Sustainability concept aims at integrating the principles of environmental conservation, social equity, and economic development into human activities. The pillars of sustainability are therefore thought to be environmental, social and economic sustainabilities. The sustainability concept as a central theme endeavours to influence the delivery of major public and private sector projects and businesses (Kannegiesser & Günther, 2014; Kannegiesser, Günther, & Autenrieb, 2015).

The sustainability of transport is said to be controlled by socio-economic, demographic and environmental megatrends. It is argued that sustainable transport should be safe, be of high-quality, and be accessible to all. Also, sustainable transport is to be ecologically sound, economically viable, and be a positive contributor to local, national and international sustainable development (DeSA, UN, 2013).

Some attempts have been made in addressing sustainability issues in the management of supply and logistics chains (Bektaş, Demir, & Laporte, 2016; Jeon, Amekudzi, & Guensler, 2010; Kennedy, Miller, Shalaby, Maclean, & Coleman, 2005; Sbihi & Eglese, 2010). These attempts include green design (Lin, 2013), green purchasing (Bai & Sarkis, 2010), green manufacturing (Lin, 2013; Shang, Lu, & Li, 2010), etc. However, less has been said about the environmental, social and economic threats resulting from climate changes due to unsustainable business activities of humans in the maritime and inland ports, transportation, logistics and supply chain (Marchant, 2010). It is in respect of this gap that the researchers want to focus their attention on the topic under study. In the area of supply and logistics chain, there is a great need for the incorporation and integration of sustainability. This is very essential and particular in road freight transportation due to the role transportation plays in the supply and logistics chain (Reisi, Aye, Rajabifard, & Ngo, 2016; Sheng & Ling-Yun, 2016).

There is a general belief by researchers that “sustainable transportation” takes its root from the concept of sustainable development with the definition given by OECD (EST, 2001; O’Brien & Vourc’h, 2001) as transportation that does not endanger public health or ecosystems and meets the needs for access consistent with (a) use of renewable resources at below their rates of regeneration, and (b) use of non-renewable resources at below the rates of development of renewable substitutes (Mi hyeon Jeon et al., 2006). The definition takes into account the pillars of sustainability which must be incorporated into the management of transportation to make it sustainable. Thus, sustainable transportation mainly focuses on reducing exhaust gasses, and these include carbon dioxide (CO₂), Sulphur dioxide (SO₂), Nitrogen Oxides (NOₓ), Particulate Matter (PM), Carbon Monoxide (CO), and (United States Environmental Protection Agency, 2016) Hydrocarbons (HC). Most studies on sustainable freight transportation concentrate on the reduction of CO₂ as it is dominant and has the greatest effects (Arnold, 2015; Kontovas, Panagakos, Psaraftis, & Stamatopoulou, 2016; Kontovas & Psaraftis, 2016; Rohács & Simongati, 2007).

Synchromodal transportation system offers better advantages of sustainability in all its three dimensions namely economic, social and environmental (Agbo et al., 2017). Economically, synchromodality impacts the total system costs, and cost compositions, total system time expense and its composition and capacity occupancies of service lines. The social impacts from synchromodal system are derived from optimized network flows and flow concentrations yielding to a reduction in road traffic, both as direct road transport and as pre- and end-haulage. Environmentally, the synchromodal concept gives a great benefit of reduction in emissions (see Figure 1) (Panagakos, 2016a, 2016b; Van Der Horst & de Langen, 2015; Zhang & Pei, 2016).
2. Statement of problem

It is an accepted fact that freight transportation has always been an integral component of economic development globally over the years. Freight transportation has emerged as one of the most crucial and most dynamic aspects of the transportation sector, where change remains constant (Agbo, Li, Zheng et al., 2017). Freight transportation is said (Leinbach & Capineri, 2007a) to be the main element supporting global commodity and more generally supply chains, complex and functionally integrated networks of production, trade and service activities that cover all stages of production from the transformation of raw materials to market distribution and after-market services (Leinbach & Capineri, 2007a). Rising cost and complexity of shipping and delivering goods is adding to profit pressures faced by manufacturers across the globe. The study of global freight transportation has taken on new dimensions and importance due to the surge in global activities over the past ten years (Leinbach & Capineri, 2007a, 2007b; Nijkamp, 2003).

The concept of division of labour currently practiced globally and the utilisation of information and communication technologies (ICT) has contributed to improvements in the transportation sector resulting in remarkable growth in worldwide freight flows (Geiger, 2016; Georgopoulou, Kakalis, Recagno, & Fozza, 2016). The sudden growth is said to be due to a set of complex production factors such as outsourcing coupled with technology explosion (e.g. use of the internet). This phenomenon has caused a closer move towards seamless transportation behaviour (Leinbach & Bowen, 2005; Mes & Iacob, 2016).

Several points of constraints have developed in the wake of activity explosion despite the advancement in the application of technology and efficient solutions to the freight transportation challenges. Lack of adequate infrastructure, high cost of freight transportation, road congestions, traffic accidents, carbon emissions, etc. are some of the problems still militating against global sustainable freight transportation. Moreover, increasing security concerns are said to be boosting costs and increasing delays in the transportation sector.

In the same manner, Outsourcing for many firms is noted to be slower presently due to transportation problems. This slow movement is forcing firms to shift to costlier but more reliable modes of transport. In this regard, modal shift is seen as a solution to the freight transportation challenges. However, for successful and efficient modal shifts in freight transportation and distribution, there is the need for increased knowledge and information sharing. There is also the need for vertical and horizontal integration of firms including organisational network consolidation due to business diversity (Aeppel, 2004).

The development of transport services and adequate infrastructures to handle freight flows has also become an important factor of economic competition between regions (De Bernardi & Sartor, 1999). The whole world is now a marketplace for freight containers, and this has generated global
competitors. It has been opined that Competition more often takes place at the level of sourcing and distribution processes rather than at the level of production. In this sense, the growth of competition has placed a necessity on firms to reduce or even eliminate stocking and distribution costs and to follow the “speed imperative” as with just-in-time (JIT) production, which reduces inventory stocks and enhances quality control by making defective work more immediately apparent and accelerates time to market (Bowen & Leinbach, 2004; Capineri, Randelli, Gips, & Economiche, 2007; Leinbach & Bowen, 2005).

Consequently, the concept of JIT has resulted in the quest for faster and more reliable choice of transportation modes to meet the demands and service levels of customers. Among all the available surface modes of transportation, the road transportation is seen as the fastest and most reliable (for short distances) despite its cost disadvantages (for long distances) and its higher level of carbon emissions (which make it environmentally unfriendly). Road freight transportation has long dominated freight flows all over the world especially in Europe and North America.

It has been estimated that by 2020, the US highway system and truck fleet will move about 18 billion tonnes of the domestic freight volume and over 1 billion tonnes of international freight volume. It is also envisaged that cargo value will triple from the current $9 to $30 trillion, and roadbound freight will constitute about 80 percent of all cargo value, both domestic and international. Similarly, in the EU-15 it has been noted that road freight transport accounted for 1,348 billion tonnes/km in 2002, with growth of over 22 percent between 1991 and 2002.

The trend of freight volume growth in developing countries is not far from the developed countries. Many developing countries are experiencing an increase in freight volume due to trade globalisation and the concept of off-shoring. Thus the need for mitigating freight transport challenges is not only limited to developed countries but developing countries as well (Leinbach & Capineri, 2007b; Psaraftis & Kontovas, 2016; Secretariat, Development, 2003).

The over-reliance on the usage of road transportation, especially between ports and its hinterland destination has since decades made the freight transportation sector less sustainable (Guo, Peeta, & Mannering, 2016; Jourquin, Beuthe, & Demilie, 1999). This is because road transportation remains the major contributor of all GHG gasses regardless of all operational and technological efforts (Norojono & Young, 2003).

Framework for developing sustainable freight transportation with relation to maritime hinterland transportation has been the focus of researchers in recent times (Hou & Geerlings, 2016; Jeon et al., 2010; Priemus, 1999; Ramani & Zietsman, 2016). One of such framework is developed by (Harry Geerlings, 1999), and according to his study, the environmental impact of transport can be addressed in four main dimensions as stated below:

(i) By reducing the total amount of transport (including organisational measures to increase load factors, etc.);

(ii) By shifting to less damaging modes of transport or forms of behaviour (e.g. driving style) (H Geerlings & Van Duin, 2012);

(iii) By reducing the impact of specific modes of transport over long-term technological means (including a more rapid diffusion of best practices in technology); and

(iv) By improving the environment regarding its spatial planning. This can reduce distances between different activities, which will eventually lead to less need for mobility.

The first three of the four factors stated above calls for an effective and efficient modal split concept and strategies at all organisational levels of the transportation sector. Over the years, modal split concepts have been developed in the freight transportation sector to deal with the prevailing challenges. Intermodal freight transportation concept was thought to be the solution to the many
challenges. The intermodal system only offers a partial solution by shifting a portion of freight volume from road to rail (Grin, Rotmans, & Schot, 2010; Priemus, Nijkamp, & D., 1999).

Intermodalism has several shortcomings which make the system less sustainable (Agbo, Li, Zheng et al., 2017). In the first instance, the intermodal system could not produce a seamless transportation system between the various modes. The system is also less agile in responding to the dynamics of the freight transportation system. The intermodal system is also less flexible in meeting the changing demands in the freight supply chain resulting in lower reliability, longer delivery times and extra transhipment costs. Furthermore, the intermodal system is less effective and less efficient in the use of transportation infrastructures. These drawbacks have certainly impacted the freight transportation system negatively thereby making it less sustainable (Bontekoning & Priemus, 2004; Marinov & Viegas, 2011).

Achieving economic, social and environmental sustainability is only possible through the integration of the various transportation modes. Interestingly, each transport mode has its own advantage comparatively. Comparative advantage of the various modes can be exploited by optimally integrating water, rail and road transport. In view of this, an optimal and beneficial model split can only be achieved through a well synchronized and integrated network (Fridell, Belhaj, Wolf, & Jerksjö, 2011; Janic, Reggiani, & Nijkamp, 1999; Márquez & Cantillo, 2013).

The economic, social and environmental/operational advantages of the different modes vary greatly and depend on the different situations and occasions or circumstances. Because of the complexities in the planning and scheduling of the various transportation modes with their associated challenges, there is the need for an innovative approach which can help integrate the modes in a network without jeopardizing the potential benefits of any of the transport modes (Caris, Macharis, & Janssens, 2008; Chatzinikolaou & Ventikos, 2016; Fernández L, De Cea Ch, & Giesen, 2004; Guo & Aultman-Hall, 2014; Witlox & Vandaele, 2005).

The concept of synchromodality has been introduced as a solution to the above-stated problems bedevilling the freight transportation sector. The concept among other things is very efficient in offering seamless and sustainable modal split with a major shift towards an increased usage of rail and inland waterway in maritime-hinterland transportation (Bontekoning & Priemus, 2004; Lucassen & Dogger, 2012; Minsaas & Psaraftis, 2016).

In this study, a mathematical model is formulated with a numerical experiment on how the concept of synchromodality could be used to attain sustainability in the freight transport industry through maritime-hinterland container transportation. Due to the newness of the concept, only a few studies have been carried out to test its operability and viability. These studies were mainly conducted in the Netherlands where the concept originates. In the meantime, no such research has been undertaken in a developing country. Thus, in our research, we attempt to apply the concept to freight transportation system in Ghana.

This research sought to provide partial solutions to the challenges of:

(i) Congestions at the ports
(ii) Road congestion
(iii) Prolonged lead-time
(iv) Environmental pollutions from trucks
(v) Transportation and logistics infrastructure under utilisation
It is worth stating that, the freight container system of the country is growing steadily due to the landlocked neighbouring countries which transport their freight containers through the ports of Ghana. There is the need to find solutions to the above-mentioned challenges. The following section presents the mathematical model formulation, numerical application of the model, results, conclusions of the study and recommendation for further research.

3. Model formulation

In this section, we discuss the mathematical model formulation for the synchromodal freight transportation. Some assumptions were made for the optimization model which are briefly state below. Also, the model notations, variables description and model constraints are presented.

Consideration is given to the synchromodal transport system between one origin and destination (OD) pair in the model. The model does not consider the rotation of barges in multiple locations at the origin or destination. The transport modes considered are three namely; barge, rail and truck. One route is considered for each transport mode. The model assumes that all transport modes have the same origin and destination and there is no transfer between modes during transportation. Different costs are allocated to different transport modes. Services, capacities, and waiting times at the terminals are also the same.

Barge and rail capacity is limited to a predefined number of services for a day and a week. This is defined by $L_{ij}$. The model incorporates no constraints for the number of trucks. However, departure time of barge and rail is determined. The departure time for truck is considered to be flexible.

The opening hours of terminals are considered when determining the departure of service. There is an allocation of penalties for earlier or later arrival at the destination though they are allowed. The penalties represent the requirement to synchronize and harmonise the “movable and non-movable” resources.

The input of the model is transportation demand and the demand pattern for each OD pair, which is from “$i$” to “$j$”. Each container batch, $b^{k(i,j)}$, is defined by a single origin “$i$”, one destination “$j$”, and “$k$” which indicates the $k$th container batches between the two points. In the $k$th container batch, arrival from origin “$i$” to destination “$j$”, container volume $Q^{k(i,j)}$ arrives at the origin terminal “$i$” at time $V_{ij}^{k(i,j)}$ and it is supposed to be delivered to the designated destination “$j$” before the due date $D_{ij}^{k(i,j)}$.

The optimization model has the departure time of each barge or rail service, and the batches flow transported by a service as the out with respect to the above input.

The notations of the model are presented below with the description = Service~Origin~and~destination; of the problem parameters and variables in the model.

| Notation | Description |
|----------|-------------|
| $m$      | Barge (Ba) and Rail (Ra) service modes; |
| $u$      | Truck service; |
| $i, j$   | Service Origin and Destination; |
| $k$      | Container batch number; |
| $k \in \{1, \ldots, N_{ij}\}; 1$ | Number “$i$” service of different modes within a day; |
| $n \in \{1, \ldots, L_{ij}\}; n$ | $n$th day in a week; $n \in \{1, \ldots, N\}$. |
The optimization model has the objective of minimizing the operational total cost, which comprises transportation cost of all the available modes, container batches waiting penalties at the terminal of origin and the destination waiting penalties.

\[
\text{Min } Z = \sum_{k,i,j \in K} \sum_{m \in \{B,a,Ra\}} \sum_{r \in \{1,...,L_{ij}\}} \sum_{n \in \{1,...,N\}} T_{m,CU} \cdot c_{m\text{CU}} + c_{m\text{CU}} \cdot \frac{Q_{t(i)}^{(k,l,j)}}{Q_{t(i)}^{(k,l,j)}} - c_{m\text{CU}} \cdot \frac{Q_{t(i)}^{(k,l,j)}}{Q_{t(i)}^{(k,l,j)}} + \sum_{k,i,j \in K} \sum_{m \in \{B,a,Ra\}} \sum_{r \in \{1,...,L_{ij}\}} \sum_{n \in \{1,...,N\}} (Q_{p(i)}^{(k,l,j)} \cdot d_{ji} + \sum_{k,i,j \in K} \sum_{m \in \{B,a,Ra\}} \sum_{r \in \{1,...,L_{ij}\}} \sum_{n \in \{1,...,N\}} (Q_{p(i)}^{(k,l,j)} - 1) \cdot B_{pt} + D_{pt})
\]
Description of model:

The total cost of barge and train service is represented in the first term in Equation (1) the transportation cost of truck service is represent by the second term. The calculation for the truck volume is done by subtracting the barge and rail volume from the total waiting cost of batch $Q^{(k,i,j)}$. The total waiting cost of batches at the original terminal is represented by the third term in the model. The waiting cost is calculated by multiplying the waiting penalties of the various batches by the waiting time of the latest shipped part of each batch. The total waiting cost of early arrival of service is denoted by the fourth term in the model. The total waiting cost for late arrival of services is represented by the fifth term. It is worth noting that the waiting penalties for transport services are incorporated into the model to enable the synchronization of the timing of the entire transport service provision with the timing of operations of inland terminals.

This constrain (2) limits the capacity per service. Operating the service number “$l$” of service mode “$m$” on day “$n$” that is $(\bar{n}^{(k,i,j)}_{m}=1)$, will require the total flow of transported batches not to be more than the maximum capacity for that service $(U_{m})$.

$$\sum_{(k,i,j) \in \mathbf{E}} \bar{e}_{min}^{(k,i,j)} \leq U_{m} \bar{\eta}_{min}^{(k,i,j)} \quad \forall (i,j) \in \mathcal{K}, m \in \{Ba,Ra\} \ l \in \{1,\ldots,L_{ij}\}, n \in \{1,\ldots,N\} \tag{2}$$

Flow constraints:

$$Q^{(k,i,j)} - \sum_{m \in \{Ba,Ra\}} \sum_{l \in \{1,\ldots,L_{ij}\}} \sum_{n \in \{1,\ldots,N\}} \bar{g}_{mln}^{(k,i,j)} \geq 0 \quad \forall (k,i,j) \in \mathcal{K} \tag{3}$$

With constraint (4), the departure time of the service is planned to be within the opening hours of each day. The opening time of the origin terminal on day “$n$” is represented by $(\nu_{m}^{0} + \bar{\nu}(n-1))$ and the closing time of the origin terminal on day “$n$” is denoted by $(\nu_{m}^{n} + \bar{\nu}(n-1))$ respectively. The departure time of number “$l$” in service of mode “$m$” on day “$n$” is to be within the opening hours of that day.

$$\nu_{m}^{0} + \bar{\nu}(n-1) \leq \nu_{m}^{(k,i,j)} \leq \nu_{m}^{n} + \bar{\nu}(n-1) \quad \forall (i,j) \in \mathcal{K}, m \in \{Ba,Ra\} \ l \in \{1,\ldots,L_{ij}\}, n \in \{1,\ldots,N\} \tag{4}$$

The waiting time for each batch from the origin, which is non-negative is presented in the constraints (5) to (7). $Q_{min}^{(k,i,j)}$ as presented in Constraint (5) demonstrates that whether the service number “$l$” of mode “$m$” on day “$n$” is chosen to transport a portion of batch $Q^{(k,i,j)}$. The arrival time of the container batch and the loading time $(VK_{m}^{(k,i,j)} + L_{m}^{(k,i,j)})$ should be earlier than the departure time of service $(\nu_{m}^{ij})$, if the above is equal to one.

$$\nu_{m}^{ij} \geq VK_{m}^{(k,i,j)} + L_{m}^{(k,i,j)} - \left(1 - Q_{min}^{(k,i,j)}\right) \quad \forall (k,i,j) \in \mathcal{K}, m \in \{Ba,Ra\}, l \in \{1,\ldots,L_{ij}\}, n \in \{1,\ldots,N\} \tag{5}$$

The constraint (6) places a limitation on the batch flow taking into consideration a particular service.

$$g_{mln}^{(k,i,j)} \leq Q_{mln}^{(k,i,j)} \quad \forall (k,i,j) \in \mathcal{K}, m \in \{1,\ldots,L_{ij}\}, n \in \{1,\ldots,N\} \tag{6}$$

Constraint (7) does not permit delay in delivery of batches to the destination terminals. In constraint (7), $(\nu_{m}^{ij} + G_{m}^{ij})$ represents the completion of the service time of the transportation. This includes transit and unloading time and this is supposed to be before the due time of the container batches.

$$D_{due}^{ij} \geq \nu_{m}^{ij} + G_{m}^{ij} - \left(1 - Q_{min}^{(k,i,j)}\right) \quad \forall (k,i,j) \in \mathcal{K}, m \in \{Ba,Ra\}, l \in \{1,\ldots,L_{ij}\}, n \in \{1,\ldots,N\} \tag{7}$$
The time of departure of the last portion of each batch \( Q^{(k,j)} \) is represented in constraints (8) to (10) where \( v^{(k,j)}_{\text{mln}} \) is equal to the time of departure of each portion of batch. Constraint (10) finds the time of departure of the last part \( v^{(k,j)} \) of specific batch \( Q^{(k,j)} \), as presented in the objective function for the calculation of the waiting penalty.

\[
    v^{(k,j)}_{\text{mln}} \geq v^{(i,j)}_{\text{mln}} - \left( 1 - Q^{(k,j)}_{\text{mln}} \right) \quad \forall (k, i, j)  \tag{8}
\]

\[
    v^{(k,j)}_{\text{mln}} \leq v^{(i,j)}_{\text{mln}} + \left( 1 - Q^{(k,j)}_{\text{mln}} \right) \quad \forall (k, i, j) \in K \tag{9}
\]

\[
    v^{(k,j)} \geq v^{(k,j)}_{\text{mln}} \quad \forall (k, i, j) \in K \tag{10}
\]

Constraints (11) and (12) describe the waiting time of early arrival. It is formulated in such a way that if there is any early arrival, then subtracting the arrival time \( \left( v^{(i,j)}_{\text{mln}} + V^{m}_{j} \right) \) from the opening time \( (v^{(i,j)}_{\text{on}} + L(n-1)) \) will give the waiting time. Constraint (12) is formulated according to constraint (11) for lateness.

\[
    \omega t^{(i,j)}_{\text{mln}} \geq 0 \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, l \in \{ 1, ..., Lij \}, n \in \{ 1, ..., N \} \tag{12}
\]

Late arrival services at the destination terminals are represented by constraints (13) to (17). The waiting is calculated by constraint (13), and \( Q^{(i,j)}_{\text{mln}} = 1 \) according to constraint (14) for lateness. The arrival of service could sometime take place after the time of opening of the terminals of destination on day “n + 1” if this happens then \( Q^{(i,j)}_{\text{mln}} = 1 \) and \( v^{(i,j)}_{\text{mln}} \leq 0 \). The waiting time is equal to 0 according to constraint (15).

\[
    \omega t^{(i,j)}_{\text{mln}} \geq \left( V^{j}_{\text{on}}(n+1) + L(n) \right) \cdot Q^{(i,j)}_{\text{mln}} - \left( v^{(i,j)}_{\text{mln}} + V^{m}_{j} \right) \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, l \in \{ 1, ..., Lij \}, n \in \{ 1, ..., N \} \tag{13}
\]

\[
    (v^{(i,j)}_{\text{on}} + L(n-1)) \cdot \left( v^{(i,j)}_{\text{mln}} + V^{m}_{j} \right) + Q^{(i,j)}_{\text{mln}} \geq 0 \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, l \in \{ 1, ..., Lij \}, n \in \{ 1, ..., N \} \tag{14}
\]

\[
    \omega t^{(i,j)}_{\text{mln}} \geq 0 \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, l \in \{ 1, ..., Lij \}, n \in \{ 1, ..., N \} \tag{15}
\]

\[
    v^{j}_{\text{on}}(n+1) + L(n) \geq v^{(i,j)}_{\text{mln}} + V^{m}_{j} \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, l \in \{ 1, ..., Lij \}, n \in \{ 1, ..., N \} \tag{16}
\]

\[
    Q^{(i,j)}_{\text{mln}} \in [0, 1] \tag{17}
\]

The services of both directions are made equal in order to balance the service schedule. This is incorporated in constraint (18).

\[
    \sum_{l \in \{1, ..., Lij\}} \hat{n}^{(j)}_{\text{mln}} = \sum_{l \in \{1, ..., Lij\}} \hat{n}^{(i,j)}_{\text{mln}} \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, n \in \{ 1, ..., N \} \tag{18}
\]

The constraint (19) contains the total number of services of mode “m” within a day.

\[
    \sum_{l \in \{1, ..., Lij\}} \hat{n}^{(i,j)}_{\text{mln}} \leq Q^{(i,j)}_{\text{mln}} \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, n \in \{ 1, ..., N \} \tag{19}
\]

Sequence of service number constraints is stated in (20) and (21). For constraint (20) the number “\( l = 1 \)” cannot be operated without the number 1 service mode \( m \) on day \( n \) being operated. The departure service is to be in sequence according to constraint (21).

\[
    \hat{n}^{(i,j)}_{\text{mln}(l+1)} \geq \hat{n}^{(i,j)}_{\text{mln}(l)} \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, l \in \{ 1, ..., Lij \}, n \in \{ 1, ..., N \} \tag{20}
\]

\[
    v^{(i,j)}_{\text{mln}(l+1)} - v^{(i,j)}_{\text{mln}}(l) \geq \hat{n}^{(i,j)}_{\text{mln}(l+1)} - \hat{n}^{(i,j)}_{\text{mln}(l)} - 2 \quad \forall (i, j) \in K, m \in \{ Ba, Ra \}, l \in \{ 1, ..., Lij \}, n \in \{ 1, ..., N \} \tag{21}
\]
Constraint (22) is for early morning departure. Constraint (23) is for late departure.

\[ \nu_{Rain} \leq [8 + \frac{1}{2} (n - 1)] + (1 - Q_{Rain}^{(i,j)}) \forall (i, j) \in K, l \in \{1, ..., Lij\}, n \in \{1, ..., N\} \]  
(22)

\[ [b + \frac{1}{2} (n - 1)] - (1 - Q_{Rain}^{(i,j)}) \leq \nu_{Rain} \forall (i, j) \in K, l \in \{1, ..., Lij\}, n \in \{1, ..., N\} \]  
(23)

\[ Q_{Rain}^{(i,j)} + Q_{Rain}^{(i,j)} = \eta_{Rain}^{(i,j)} \forall (i, j) \in K, l \in \{1, ..., Lij\}, n \in \{1, ..., N\} \]  
(24)

\[ Q_{min}^{(i,j)}, Q_{min}^{(i,j)} \in [0, 1] \]  
(25)

Other Constraints:

\[ z_{min}^{(k,b)(i,j)}, \nu_{min}^{(k,b)(i,j)}, \nu^{(k,b)(i,j)} \geq 0 \]  
(26)

\[ \eta_{min}^{(i,j)}, Q_{min}^{(k,b)(i,j)} \in [0, 1] \]  
(27)

### 3.1. Case study and numerical experiment

The operability of the synchromodality concept (Agbo et al., 2017) in Ghana is numerically experimented using the above-discussed model. A synchromodal network is designed between the maritime port of Tema and inland barge port at Yapei in the northern region of Ghana. Currently, the railway service does not extend to the Yapei barge port but ends about half way at Kumasi. However, plans are underway for the extension of the railway line from Kumasi to Tamale, and from Tamale through Bolgatanga to Paga and Burkina Faso. This study assumes the existence of the railway services on the said corridor for the purposes of the experiment.

The country is chosen for the case study for number of reasons. In the first instance, the country is geographically located near the sea with two major seaports which are linked with inland waterway. This offers inland navigation to the hinterlands of the country. Secondly, there is a surge in the growth of container freight transportation which is facilitated by the container demand from the

| Years | Vessel call (Units) | Total Cargo traffic | Export | Import | Transit | Transhipment | Container traffic |
|-------|---------------------|---------------------|--------|--------|---------|--------------|------------------|
| 2003  | 1,172               | 7,391,268           | 809,589| 5,490,893| 885,093 | 138,520      | 305,868          |
| 2004  | 1,381               | 8,447,655           | 1,072,006| 6,403,422| 764,128 | 71,082       | 342,882          |
| 2005  | 1,643               | 9,249,977           | 1,182,469| 6,936,688| 875,325 | 155,815      | 392,761          |
| 2006  | 1,994               | 8,046,838           | 955,084| 5,675,027| 887,589 | 339,841      | 425,408          |
| 2007  | 1,672               | 8,378,682           | 1,099,094| 6,120,583| 843,656 | 119,209      | 489,147          |
| 2008  | 1,568               | 8,727,049           | 1,099,094| 6,259,412| 864,307 | 195,326      | 555,009          |
| 2009  | 1,634               | 7,406,490           | 1,305,451| 5,694,280| 509,124 | 192,565      | 525,694          |
| 2010  | 1,787               | 8,696,951           | 981,075| 6,823,488| 447,071 | 236,615      | 590,147          |
| 2011  | 1,667               | 10,748,943          | 1,154,826| 8,431,531| 614,078 | 171,195      | 756,899          |
| 2012  | 1,521               | 11,468,962          | 1,532,139| 9,383,462| 530,457 | 50,403       | 824,238          |
| 2013  | 1,553               | 12,180,615          | 1,477,390| 10,014,243| 620,668 | 51,748       | 841,989          |
| 2014  | 1,504               | 11,126,355          | 1,463,273| 8,922,550| 577,277 | 163,305      | 732,382          |
| 2015  | 1,514               | 12,145,496          | 1,303,090| 10,043,146| 722,508 | 76,752       | 782,502          |
3.2. Freight transportation situation in Ghana

Ghana's maritime trade has seen significant development over the years (Ghana Ports & Harbour Authority, 2007). Ghana has two major maritime ports namely, the Tema Port and the Takoradi Port. These ports are regulated by the GPHA. The shipping industry in Ghana with major entities such as the ship-owners Agents Association of Ghana (SOAG) and the Ghana Institute of Freight Forwarders (GIFF) has contributed immensely to the economic and trade development in Ghana. The Ghana Shippers’ Council is formed with the sole aim of protecting and promoting the interest of shippers in Ghana. The Council ensures conducive and transparent environment to maintain business efficiently at the ports (Ghana Ports & Harbour Authority, 2005, 2007).

The throughput of Ghana’s cargo has seen a great increase from 8,727,049 million metric tonnes in 2008 to 12,145,496 million metric tonnes in 2015 (Ghana Ports & Harbour Authority, 2016a, 2016b). This drastic growth in cargo throughput is attributed to the country's population increase. The phenomenon has significantly impacted the consumption rate of both local and exotic goods. Coupled with this, the remarkable use of Ghana’s maritime ports by the neighbouring landlocked countries—Burkina Faso, Mali, and Niger – has played a major role in the cargo growth (Ghana Ports & Harbour Authority, 2016a, 2016b) (Tables 1–2).

According to Roso (Kovacs, Spens, & Roso, 2008), the increase in population and a greater economic activity has a direct bearing on maritime container freight transport. This situation consequently results in land surface freight transport growth. The phenomenal increment is, however, affecting the operations of ports and ports business in some ways. On the one hand, the situation is creating lack of space at the ports areas for smooth and efficient operations. On the contrary, the condition is increasing road congestion due to more usage of trucks which is culminating in increased lead-time. These unfavourable conditions are currently prevailing at the maritime ports of Ghana (Ghana Ports & Harbour Authority, 2005).

To ensure healthy competition with neighbouring ports of the country, there is the need for proactive measures to transport cargo from the maritime ports to the hinterlands and the landlocked neighbouring countries. As postulated by Caesar, Riese, and Seitz (2007) (Caesar et al., 2007), the means whereby people shaped the landscape through time demands imperativeness for business and governments concerns regarding sustainability of food, water, transport, energy, etc.
Table 3. Data for the numerical analysis

| Mode     | Cost ($/TEU) | Waiting penalty ($/hr) | Capacity (TEU) | Service no./day | Loading/unloading (hr) | Transit (hr) |
|----------|--------------|------------------------|----------------|-----------------|------------------------|--------------|
|          |              |                        |                |                 | Tema-Yapei | Yapei-Tema | Tema-Yapei | Yapei-Tema |
| Barge    | 64           | 113                    | 45             | 4               | 1.2        | 1.2       | 10         | 10         |
| Train    | 85           | 142                    | 115            | 1               | 1          | 4         | 4          | 4          |
| Truck    | 128          | –                      | –              | –               | –          | –         | –          | –          |

Source: Field data.

Figure 2. Ghana river map (2013).

Figure 3. Synchromodal network.
The model is applied using the presented data (Table 3) to find an optimal schedule for the services of rail and barge on the chosen corridor. In the study, we used Mixed Integer Linear Programming to solve the optimisation problem. The CPLEX 12.0 Software is used in finding solutions to the optimisation problem. OriginPro 9.0, 32-Bit Software is used in plotting the results of the optimisation (Figures 4–8).

The integrated transportation network designed for the optimisation is shown in Figures 2 and 3 below. As stated earlier, there is no effective intermodal freight transportation system in operation currently in Ghana. All freight container transportation from the sea port to the hinterland is done via road. Furthermore, though all the three modes selected for the case study are in operation, they
operate individually as single modes. In this study, two different cases were considered for the comparison of the results of the synchromodal service network. In the first case, barge and rail service coordination are not considered. Within a day, four barge services are assumed, starting from Monday to Sunday respectively. Rail service is also assumed to be once daily, from Monday to Saturday, in both directions of the transport network. The barge is planned to depart at the following times: 8:00, 12:00, 15:00 and 22:00. The rail departure is scheduled at 20:00. Consideration is given to truck services in the absence of rail and barge services.
In the second case, the schedules for barge and rail services are optimized. The barge schedule is optimized first and then the rail schedule. The modelling results are presented in the Figures 4–8 below. The synchromodal service design yielded a result of $92,937 difference, which is a great cost saving of about 22%. The savings obviously come from the less use of trucks as considered in the case of the integrated service schedule. Again, it is observed that the penalty for waiting at the terminal of origin is considerably reduced. When compared with the second case which is sequential in nature, the synchromodal service offers a cost savings of about 8%.

The synchromodal service design offers better modal split by using barge and rail services in this study. This confirms that the concept is more sustainable since fewer truck services are required offering cost savings, efficiency, effectiveness, and flexibility.

The objective of the synchromodal freight transportation system is to introduce efficiency and effectiveness into the intermodal transportation system (Agbo, Li, Atombo et al., 2017). This is achieved through flexible mode free booking, efficient transport resources utilisation and better modal split. These help in ensuring total transportation sustainability in the overall transportation system.

From the numerical experiment, it is evident that the synchromodal transport service performed better in all respects than the unimodal road transport and the traditional intermodal transport systems. The transport cost for the synchromodal service is far less than that of the unimodal and intermodal services. This is in one hand due to the minimum usage of road transport, and on the other hand due to the lower waiting penalty at origin and destination for the barge and train services. The introduction of the waiting penalties at the origin and destination will definitely compel service operators to be time conscious, thereby avoiding the penalties. This will result in lower total service cost.

One of the advantages offered by the synchromodal freight transportation system is the better modal split in favour of rail and barge services (Agbo, Li, Atombo et al., 2017). This benefit is shown in this study. In the case of unimodal service, which is basically road transport service, about 97% of containers transported are done by road. The model in this study raised the barge services to about 56% and the train service to 27% respectively. This helped in achieving better modal split which enhances environmental sustainability since few trucks are used. Capacity utilisation is also an essential factor when dealing with synchromodality. With the model under consideration, the utilisation capacity for rail and barge is increased to an appreciable level in the synchromodal service.

4. Conclusion and recommendation for further research
The concept of synchromodal transportation system is obviously new and still at its developmental stage. Few studies have been conducted on the topic, largely in the Netherlands where the concept
originates. The concept offers better utilization of transport infrastructure and modes between maritime and hinterland ports by using mostly barge and rail services, and trucks sparingly, to provide a more flexible, more economical and more sustainable way of freight transportation.

In this study, a brief background to the concept of synchromodality is given with emphasis on sustainability in freight transportation system and a mathematical model is formulated. Certain assumptions were made where necessary, during the model formulation. A feasibility study was conducted to see how applicable the concept is in the chosen country. One major factor for the consideration of synchromodality for a given corridor in a given country is the geographical location and geographical features of that corridor. There must be a sea or maritime port, navigable river or inland waterway, and a railway system, in addition to the most common type of transportation mode-road transport. Ghana has two maritime ports, three operational barge ports, an operational railway system in the southern sector, and a large road network. Currently, about 97% of the country’s freight transportation is done by road. This study considers introducing synchromodality concept into the transportation system of the country.

Data is used for numerical experiments using the mathematical model. The research results show that the implementation of synchromodality concept into the freight transportation system of a country has a great potential of improving total transportation and service cost, and most of all, help in the reduction of road transport emissions and road congestions for great environmental benefits. Other benefits to be derived from the implementation of the new concept are envisaged to be a reduction in road accidents since fewer trucks are going to be deployed during freight transportation. Coupled with this, the level of noise pollution will reduce drastically because of freight truck minimization. It is worth stating that, the main focus of this research is about how to ensure sustainability in the freight transportation sector by implementing the concept of synchromodality which offers better modal split in favour of barge and rail transportation.

The mathematical model formulation in this study did not factor in the amount of carbon emissions to be generated from the use of each transport mode per the freight demand. The results were based on the modal split, and it is obvious that the use of fewer trucks produces lesser carbon emissions and other associated pollutants. The focus was more on modal split which favours emission reduction. It is therefore recommended that future research considers calculations on actual amount of carbon emission reductions.

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**Author details**
Aaron Agbenyegah Agbo1
E-mail: aaron.agbo2008@yahoo.com
ORCID ID: http://orcid.org/0000-0003-3140-0894
Yanwei Zhang2
E-mail: zytg@wut.edu.cn

1 Department of Logistics and Transportation Services, Ghana Prisons Service, Prisons Headquarters, Cantonments, Accra, Ghana.
2 School of Logistics Engineering, Wuhan University of Technology, Wuhan 430070, China.

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