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Cold chain for sustainable infrastructure planning

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Abstract

Cold chains improve the safety and quality of perishable goods. Incorrect storage temperatures can cause textural degradation, discoloration, bruising, and microbiological growth. Cold chain logistics involves transporting temperature-controlled items like food, beverages, and biopharmaceuticals. In this paper we outline challenges and opportunities via a literature review of 'cold chain' research agenda with a specific focus on transportation and logistics. Previous attempts have been made in addressing the technological aspects of the cold chains, such as efficient energy system and sustainable refrigeration technologies in response to, for instance, delivering a low temperature-controlled products. Our proposed approach here is to set up the ground for logistics and transportation studies and aid the development of cold chain modelling and simulation. We introduce computer modelling framework, using capacity, roles, interaction and organization (CRIO) meta model to response to sustainable cold chain. A conceptual design of an agent-based model using Scottish salmon logistics network was introduced.

Keywords: Cold chain; Logistics; Sustainability; Agent based model; UK

1. Introduction

The increasing environmental impact of cold chain has received attention from industry and academics, who gradually understanding its importance in the broader sense in responding to the global sustainable development goals (Peters 2018). The central argument was that within the increasing climate temperature due to global warming, the role of a low-temperature controlled supply chain will be more significant to ensure the supply and delivery of food and medicine; and as much as to minimize waste due to un-conditioned temperature-wise post-harvest agriculture products (UKERC 2021). The research agenda is aligned with the global initiative to celebrate the importance of cold

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chain (United Nations Environment Programme (UNEP) 2020), and even receiving increasing prominence following the pandemic, where duly cold chain vaccine distribution can effectively be enforced (Sayin and Peters 2020). Refrigeration technologies and their environmental impact have long been established via the International Institution of Refrigeration (www.iifiir.org) and low temperature-controlled distribution industrial association, such as the one in the UK, which recently known as Cold Chain Federation (www.coldchainfederation.org.uk) since 2019. Cold chain as a concept will define the future of food safety and security, circular economy production with sustainable operations, and fairness to farmers and wider stakeholders along the chain (Sayin and Peters 2021). There are certain questions remains when referring to infrastructure planning: what are the key components of cold chain? What makes cold chain unsustainable? Where is cold chain located within supply chain management? And ultimately, how are the transport and logistics components of cold chain addressed within the sustainable development paradigm?

This paper forms part of several on-going cold chain UK funded projects to address sustainable cold chain, zero-emission cold chain, and center of excellence for sustainable cooling and cold chains initiatives where modelling and simulation serves as focus segment of interest. It begins with semi-systematic review – a mixture of rapid literature review and regular consultation with research consortium comprises of experienced researchers and industrial partners – and introductory coverage of the transport and logistics modelling environment with several discussions supplied from our previous and on-going studies in sustainable road freight. A conceptual model design was introduced to discuss and to address the cold chain research agenda.

1.1. Background

One of the key components of cold chain is refrigeration. Many early studies on refrigeration technologies have been well documented by the *Institut International Du Froid* - International Institute of Refrigeration (IIF-IIR) (est.1908), which then formally taken by Elsevier peer-reviewed publication and known as 'International Journal of Refrigeration'. The particular attention given to transportation by the institution was driven by the expansion of the chilled and quick-frozen foods market (James et al. 2006) as also well observed in food supply chain management studies (Smith and Sparks 2004). One of the early studies quantifies refrigerated transport containers which are embedded in marine transport (estimated at about 550k) and road vehicles (1.2 million), to ensure smooth delivery of the required products' hygiene and safety, while considering its energy consumption (IIF-IIR 2003). Most of the transport refrigeration units modelled, were electrically powered, either by main transport engine with alternator or supported with portable diesel generator sets attached to them. Exception was on air transport, where 'dry ice' has been generally used. The electrical power requirement for chilled versus frozen transport goods varied by demand to control temperature (including heating, which consequently requires more power and energy).

A recent study led by IIF-IIR has established the environmental impact of global cold chain. The study has been repeated at regular interval to monitor global refrigeration used and measured its impact on the environment. 3.4 million refrigerated vehicles, 449 million m^3 cold storages volumes, 66k km (linear meters) of refrigerated display cabinets in supermarkets, and 1.967 billion units of household refrigerators and freezers were modelled to demonstrate an uninterrupted system of temperature-controlled transport and storage of refrigerated food products between upstream producers and final consumers (Sarr et al. 2021a). The study emphasized the importance of food refrigeration from farm to fork – via a scenario in which the cold chain in all countries is brought to the same level of equipment and performance as the existing in developed countries – in reducing CO_2 emissions (estimated at 50%) and food losses (55%) as policy agenda (Sarr et al. 2021b). Notwithstanding this estimation and policy recommendation to promote fridge market growth, there is very little known on how this change will impact the supply chain distribution and, ultimately, how the response to this change will reflect in transport and logistics systems and its energy resources. While addressing this knowledge gap would benefit global society, we wish to bring about the case of the UK, where much of the energy system has gradually moved towards renewable resources. The UK is indeed considered as one of the few countries in the world identified as using predominantly renewable resources (assumed at 0.4 kg eq CO_2/kWh – the second out of four-band scale; 1^{st} band was nuclear powered with 0.15 kg eq CO_2/kWh; 3^{rd} fuel, 0.6 kg eq CO_2/kWh (most countries power resources); and 4^{th} coal at 1.6 kg eq CO_2/kWh) in powering the cold chain (Sarr et al. 2021c). The hope is to outline the pathway for many to adopt such an approach to meet the net zero emission agenda in a similar fashion as the UK industry (Southall 2021).

UK cold chain studies toward net zero have only recently began following the formation of Cold Chain Federation. The formation was originated from long established UK-based industrial association of temperature control storage and distribution trade network, which recently engaged with academics to address the net zero agenda (Cold Chain Federation 2021a). Some of the key discussions evolved into several industrial-led white papers, a series of consulted guidebooks for the sector towards meeting the net zero agenda. This guidebook illustrates the sector's actors' reflection of the subject to not only addressing technical and operational problems but also behavioral integration to meet whole system energy savings. Acknowledgement was given to the lifecycle assessment (LCA) paradigm, for instance, the cold chain of New Zealand lamb consumed in UK, where processing (3%) and transport (5%) contribute a relatively small proportion of emission as compared to farming (80%) and consumers (12%), as reported in Ledgard et al. (2011) (Cold Chain Federation 2020). We view this acknowledgement from the association rather optimistic and noted there are more recent development in ways to approach LCA. A study based on agri-biosystem research group demonstrated that LCA can be made incompatible by author-derived decisions and assumptions, especially on simplified cases (Yan et al. 2011) and missing the importance of social dimension (Chen and Holden 2017). In addition, recent LCA cold chain studies demonstrate the GHG emissions' variations from different type of food products (Dong and Miller 2021) and high energy dependent of cold warehouse operations (Dong et al. 2022).

Another white paper discussed at the Cold Chain Federation consultation relates to the definition of the net zero cold chain, with dependencies on key agents' behavior (i.e. individuals, buildings and vehicles) across the cold chain sectors (i.e. agriculture, health, manufacturing, logistics and retail) in order to set own targets with given Government guidance (Cold Chain Federation 2021b). There are three other white papers to shape the UK's net zero cold chain to cover road vehicles, cold stores and cold chain ecosystem, which can be described as an on-going consultation process between industrial actors and academics to lay the ground to the net zero cold chain pathway. The first UK Cold Chain consultation process on road vehicles elicited several key indicators of change, such as the environmental assessment of the Transport Refrigerated Units (TRUs), categorized as a non-road mobile machinery; current vehicle types and cooling technologies including refrigerants; policy recommendations to reduce emissions; and ultimately research questions on powering future refrigerated transport in the transition of transport infrastructure electrification (Cold Chain Federation 2021c). The vision of zero emission refrigerated trailer – with emerging innovative study, e.g. CENEX (2021), was clear from the consultation document, however, several key inquiries have been raised including: How will the electric charging network operate? Will competitors allow each other to charge at their respective depots? How will grid capacity expand to allow the mass installation of energy hungry chargers? In addition, although widespread adoption of emission-free heavy goods vehicle (HGV) engines is still some way off, switching to separately powered, emission-free refrigerated trailers represents a "no-regret" intervention opportunity (as it will be required in the case of emission-free HGVs) which will reduce emissions earlier and lead the way in decarbonizing UK transport (Cold Chain Federation 2021c). Next, ultimately is where, how, when and in what ways should transport and logistics research response to any of those queries?

1.2. Policy and other dimensions

Before we move on to the review of cold chain studies, it may be worth to show parallel work of global initiatives to put cold chain as the focus of sustainable development, not from the industrial perspective as previously discussed but from the global societal dimension. Continuing observations from the Institute of Refrigeration (IIF-IIR) and United Nations Environment Program (UNEP) highlighted the extension of the Paris Agreement (post Kyoto protocol) focus – limit to 1.5°C temperature increase – via 'Reducing CO_2 emissions' research, with another policy agenda in Kigali Agreement (post Montreal protocol), on issues of refrigerants leakage impact – limit hydrofluorocarbon (HFC) to less than 15% – which depleting ozone holes of global atmosphere, and UN Sustainable Development Goals. Cold chain is envisioned as enhancing incomes for fisherman and farmers; reducing food waste; and securing medical (requiring cold chain) supplies to remote communities (Peters 2018). Studies to capture groundwork of global cold chains require a baseline data collection framework to capture demand and strategies in different environments and promote to international governments. Efforts to address that has commenced (Peters et al. 2020) and been promoted (Kumar et al. 2022) with early results providing a clearer picture of the real societal challenges in achieving sustainable cold chain in developing environments (Debnath et al. 2021). Some issues raised include differences in food product preferences by different communities, e.g. dairy products as opposed to meat in rural India as reported in Debnath et al. (2021), and much wider cooling product requirements in different sectors such as, agriculture: food production, livestock, and fisheries; post-harvest produce management: refrigeration, transport, and food processing; health: vaccine and other temperature sensitive pharmaceutical products and blood storage, transport, space cooling, and comfort; and transport: cars, buses, vans, and freight trucks.

At the recent 2022 United Nations Climate Change Conference meeting (COP27), the importance of cold chain was highlighted as key life tool towards responding sustainably of growing global food demand. Food loss from the lack of cooling could feed 1 billion people and vaccine loss could have saved 1.5 billion lives annually (Centre for Sustainable Cooling). The recent formation of Africa Centre for Sustainable Cooling and Cold Chain (ACES) has demonstrated the commitment made from all cold chain actors and wider societies.

2. Characterising cold chain in transport and logistics studies

There are few cold chain focus studies in the transport and logistics research domain, some of notable previous works are studies on food supply chain management, see for instance edited book by Bourlakis and Weightman (2004). This is in contrast with food and agriculture sciences research domain where the topic has already been well covered to a good detail, see for example Mercier et al. (2017) study which outlines the current state of commercial cold chains. Similarly, Han et al. (2021) envisages low carbon strategies toward future cold chain logistics. Transport refrigeration technologies, however, have been a subject of interest to the businesses as the reliance on fossil fuel-based transport operation persists (Bengherby et al 2015). The transport refrigeration unit emits between 3- and 15-tons CO_2 per year (equivalent to between 2 and 9 average UK cars), 16 times more nitrogen oxide (NO_x) and 40 times more particulate matter (PM) (CENEX, 2021). The smart, green and integrated policy for freight (Aditjandra 2018) has started to enter wider interdisciplinary research domain such as energy management and environmental, food and agricultural sciences.

The development of temperature-controlled supply chain in UK was described by Smith and Sparks (2004) using Tesco, the largest UK retail supermarket chain with over 4000 outlets and over 300k staff. The review demonstrates evolution of food policy, refrigeration technologies and food handling, since unregulated food sales were around in the UK, up to the period when food shelf life had increased from 5 to 11 days. Three distinctive characteristics of the chain-system highlighted were: costs (a multi temperature trailer was over three times the price of ambient trailer then; cold warehouses were twice the price of ambient ones), food safety (enforcement of Food Safety Act 1990) and partnerships (very much represented with the strong formation of Cold Chain Federation as discussed in the previous section). Despite unique characteristics of the chain, the basic supply configuration of the temperature-controlled channel was not considered very different to those ordinary retail distribution channel (Ibid).

One of the first food logistics survey, including refrigerated (cold) chain, was done in the UK to characterize food transportation impact on the environment, via fuel consumption efficiency, and benchmarking the UK food supply chain (McKinnon et al. 2003). The role of transport refrigeration was oversighted then, but note was made on the fact that 80% of the total ton-km of food distribution delivered by articulated (ARTIC) vehicle with 32-ton capacity or over (Tassou et al. 2009). Fig. 1 illustrates cold chain logistics system with four linked key system components in precooling, warehouse refrigeration, refrigerated transport and retail/catering/domestic refrigeration. Cold chain moves product from upstream to downstream of the supply and distribution network. Throughout the chain, the physical, chemical, and biological changes of fresh produce are affected by intrinsic (thermal and moisture diffusion of food) and extrinsic factors (compression, impacts, vibrations, temperature, concentration of ethylene, O_2 and CO_2) (Han et al. 2021). Taking example of meat cold chain as illustrated in Fig. 1, after livestock slaughtered, pork, beef and chicken were entering cold chain process where pre-cooling took place, before then some of the food went to frozen stage and some went to chilled stage at the cold storage and tagged with place of origin. From that stage, the products were transported, with potential consolidation with other type of produce, such as fresh fruit and vegetable (so optimising truck load capacity) to a distribution centre/ logistics park to be either further treated or better packaged to add value, to then transported (frozen/chill) to another place of cold storage where all the products are ready for sale. This place of sale, where consolidation with fish/crustaceans/aquatic products happened, can be in the form of supermarkets, wholesalers – to supply hotel, restaurant and catering (HORECA), and refrigerated delivery services. From the place of sale to the consumer, the cold chain products were coordinated individually to finally arrive at domestic refrigeration.

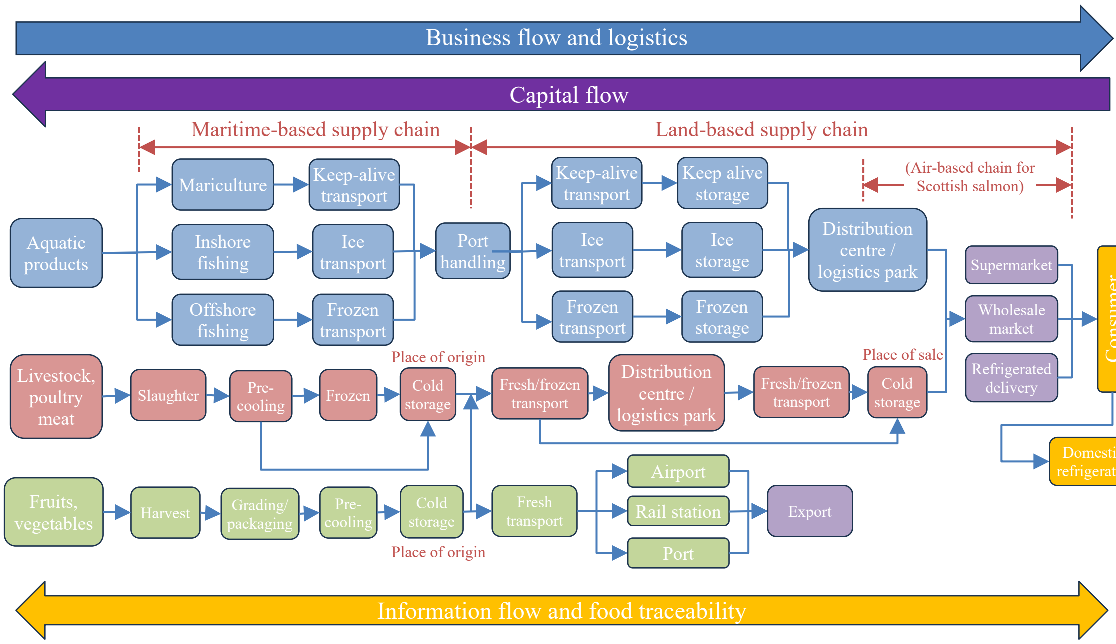

Fig. 1. Cold chain logistics system for fresh agricultural products (Adapted from Han et al. 2021).

A systematic review of about 50 academic papers on cold chain written by Fan et al. (2020) identifies five different stream of focus interest studies, which include monitoring and control (of shelf-life products) (41%), transport operations (27%), reefer design and characteristics (18%), terminal (12%), and general reefer logistics (2%). The review concluded that, generally cold (supply management or logistics) chain studies are aimed at addressing cost efficiency, product quality and environmental impact and most studies reviewed were international in scale using sea vessel containers transport (reefer). Another review study has filtered over 900 SCOPUS and ISI Web of Knowledge recordings plus experts recommendation into 132 selected papers; and demonstrated an increasing demand of ‘cold chain’ or ‘cold chains’, because of significant demand growth in reefer containers (Castelein et al. 2020). This clustering literature exercise points to several study strands, with highly specialized, technical studies on product characteristics and quality preservation, monitoring and control, refrigeration technology, and temperature management – confirming the outputs of Fan et al. (2020) studies. Organizational aspects of many of the reviewed studies deemed missing and raised as a research gap (Castelein et al. 2020). A US based study involving 250 third party cold chain logistics’ companies representing U$5.7 billion market identifies five pillars of organizational innovativeness within the sector in creativity, openness, future orientation, risk taking and pro-activeness (Johnson 2020). The study demonstrates generic organizational issues faced by the cold chain logistics sector and would benefit from well-established logistics and supply chain management organizational studies. A comprehensive bibliometric and network analysis, evaluating over 1000 food cold chain published articles over the past 25 years by Shashi et al (2021) demonstrated four underlying research stream in the topic: (Cluster 1) application of RFID technologies in monitoring temperature controlled products; (Cluster 2) production and operation planning models; (Cluster 3) post-harvest waste, causes of postharvest wastage and perishable inventory ordering policies and models; and (Cluster 4) critical issues in food cold chain, such as energy, sustainability and best practices. Much of those studies reviewed were treating cold chain as another type of supply chain operation and logistics using ordinary supply configuration. The question raised then is how this is true with the changing temperature due to climate change and the transition to electrification.

Several technological and operational cold chain studies demonstrated new focus of interest to reveal the true impact of cold chain. Bagheri et al. (2017) investigated real-time performance of typical refrigerated trailers (battery-powered vapour compression refrigeration (VCR) system – the most commonly used system globally estimated at 80%) delivering daily-based food (dairy products) delivery in Vancouver, British Columbia, Canada. The study found that battery powered VCR is greener than diesel-fueled power VCR. Stellingwerf et al. (2018) modelled a temperature-controlled food distribution, using one-month Dutch frozen food company data, with vehicle routing objective optimisation problem (VRP). The study run three different models: (1) the standard VRP model, which minimizes total distance, (2) the load dependent VRP (LDVRP), which takes account the load of the vehicle and minimizes motive emissions, and (3) the temperature-controlled version of the LDVRP model (TCLDVRP), which minimizes total emissions by accounting for both the load of the vehicle and refrigeration. Key cold chain variables assumption such as thermal efficiency and refrigerant emissions were derived from known studies as discussed above (Mckinnon et al 2003 and Tassou et al 2009). One of the study findings was thermal emissions have negative relationship with average speed. Another study using three different land use settings of urban, suburban and motorway, known as London drive cycle speed profile, investigated the emissions of refrigerated vans – typically 3.5-ton gross weight vehicles equipped with temperature-controlled units called Transport Refrigeration Units (TRUs) (Yang et al 2021). The study uses PHEM (Passenger car and Heavy-duty Emission Model) to estimate the emission from the vehicle operation which typically used for grocery home deliveries and discovered that vans with TRUs emitted 15% higher CO_2 and 18% NO_x emissions than standard vehicles. Carbon tax policy experiment on cold chain operations in Queensland, Australia (Babagolzadeh et al, 2020) however, demonstrates non-significant influence to lower emissions but combination of light and medium duty vehicles used were contributing to cost and emissions savings.

3. Modelling and simulation components for cold chain

Logistics and supply chain modelling studies are traditionally aimed at minimizing cost, as this objective very much represents general business objectives. Only since the acknowledgement of increasing social and environmental impact of logistics operations, modelling and simulation started to touch other objectives, such as driven by environmental and social focus to reflect on the sustainability agenda as prompted since the Brundtland report in early 1990s. Since then, its application to different industrial sectors has been fruitful, and this is especially the case of operational research which rely on data simulation or modelling to support decision making – please see Brandenburg et al. (2014), for review of modelling typology.

As for cold chain, the modelling efforts goes into several numerical simulation of different type of operations of refrigerated vehicles considering parameters such as drive cycle, material design and geometry, refrigeration system technology used, energy production and consumption, product characteristics and ambient temperature (Maiorino et al. 2021). A recent review of cold chain vehicle routing studies show that the majority of cold chain logistic studies use cost modelling to optimize either one or two objectives on transportation cost, food quality and environment (Awad et al. 2020). Parameters typically used include time, temperature, door opening, vibration, humidity, CO_2 concentration, and air; on several food types including meat, strawberry, fruit and vegetable products and other perishable goods (ibid). Another study looking at determining cold chain decision-making behavior, via Delphi survey and run on fuzzy logic modelling framework, demonstrates several factors affecting food quality and safety, including packaging, storage specifications and loading capacity, handling issue and inventory rotation, cold transportation, delivery delay, traceability, well-trained staff (to reduce waste), technical issues, consumption, and hygiene requirements of physical condition (Turan and Ozturkoglu 2021).

Cold transportation in logistics and transportation studies are very much an operation of another type of vehicle, which in this case is known as refrigerated transport vehicle. This difference in characteristics has received little acknowledgment as reflected from the UK Continuing Survey of Road Goods Transport, where refrigerated transport has not been reviewed separately from the rest of the goods vehicle at annual national freight statistics. Notwithstanding omission of this fact by the UK Department of Transport, studies on refrigeration transport technologies has been well described in James et al. (2006). Specific note given to a good understanding of the technological requirement, such as heat and mass transfer in responding to food safety, of chilled and frozen goods. One of the critical papers on refrigerated transport draws the detail specification of energy consumption of refrigerated vehicle (Tassou et al. 2009). The study uses previous studies (i.e. McKinnon et al. 2003) and interviews with (refrigerated) transport operators to elicit the characteristics of diesel-fueled refrigerated truck use. The study finds that UK refrigerated food distribution is emitting between 48 – 115 gCO_2/pallet-km (Tassou et al. 2009). The lower emission derived from ARTIC refrigerated transport in delivering single primary distribution and the higher emission from rigid refrigerated trucks delivering multidrop tertiary and mixed distribution. UK food distribution flows can go through three level channels: primary, secondary and tertiary (McKinnon 2004); primary distribution links food movement/delivery from factories/farms to regional distribution centers (RDC), either directly or via primary consolidation centers; secondary distribution links distribution from RDCs to supermarkets' chains/shops; and tertiary distribution links from (large) wholesale depots to independent retailers, including food service sector (HORECA)/catering outlets and local wholesale/cash and carry (ibid).

TRU is the most commonly detached refrigerated transport unit used in the UK. This unit must pass certification 'ATP agreement' – the Agreement on the International Carriage of Perishable Foodstuffs and on the Special Equipment to be Used for such Carriage (ATP) enacted by the United Nations Economic Committee for Europe in 1970 and enforced since 1976 (https://unece.org/text-and-status-agreement) – by single organization, Cambridge Refrigeration Technology, endorsed by the government to license each TRUs in the UK – similar to the annual MOT (Ministry of Transport) test of vehicle safety, roadworthiness and exhaust emissions for personal vehicles but lasting longer (six years which can be extended by another three). In the UK, around 1500 ATP certificates are issued each year with a 1.5% annual increase rate (Cambridge Refrigeration Technology; Tassou et al. 2012; The ACR Journal 2015). Using that figure, our estimate for today is that about 95k-100k refrigerated transport have been registered and circulated in the UK. This is greater than that estimated by Foster et al. (2022), using figures from Cold Chain Federation with 75k vehicles (30k artic; 15k rigid; and 25k vans). Note, this does not include overseas registered refrigerated trucks entering the UK. The question is then whether this rate of growth is sufficient to response to net zero emission by 2050; and if this is applicable to different settings, e.g. developing environment, land-locked countries, etc.

There are 3 major types of refrigerated vehicles: small converted vans (up to 3.5 tons), rigid trucks (up to 32 tons) and ARTIC trucks (up to 44 tons). 80% of those trucks are using diesel fuel powered vapour compression refrigeration system which generally use refrigerant with high global warming potential (GWP), such as R404A (Maiorino et al. 2021). In addition, the refrigerated container uses insulation material which deteriorates with time and increase energy consumption (Tassou et al. 2012). Similarly, refrigerant leakage is another issue needs addressing as this add 30% extra emissions (Francis et al. 2019).

Most of the refrigerated transport fleets in the UK are diesel powered with 66% of total ton-km goods movement delivered by artic vehicles (Department for Transport 2021) – this is a decrease from 80% of total goods moved by artic as observed in 2004 (Tassou et al. 2012). It was notable that consignment to food products tend to be space-constraint rather than weight constraint (McKinnon et al. 2003). Fuel consumption rate for a semi-trailer refrigeration unit at 30°C environment (typical tropical countries) is between 0.5 – 2.5 litter/hour, with lower fuel consumption required to control ambient temperature at +3°C and higher fuel consumption for frozen temperature at -25°C (Tassou et al. 2012). Most recent estimate of refrigeration for road transport emission in UK adopts 3 litter/hour rate at full capacity and with 100% compressor run time as reported in Foster et al. (2022).

4. Exiting computer model toward cold chain for infrastructure planning studies

The Centre for Sustainable Road Freight - CSRF (https://www.csrf.ac.uk) have recently developed a modelling environment and object library to support agent-based modelling experiments, named: MILES (Multimodal Integrated Logistics of Environment Systems), it takes the form of an extensive library of Java objects and classes, together with logistics algorithms written to exercise these classes and provide a reusable, scalable environment for agent-based modelling that is based on open-source building blocks and can also be run on a remote server, allowing consideration of large-scale, highly coupled problems that take significant computational resource to run. MILES is one of a few recently developed digital platform within the realm of digital twins since popularity of freight transport modelling was drawn at international level (de Jong et al. 2013). Data & Analytics Facility for National Infrastructure (DAFNI) was another known UK-based established platform with several applications in water distribution resources, agricultural land-use changes, and passenger transport operations.

4.1. Vaccine distribution application – national cold chain simulation

As part of its logistics code suite, MILES already includes an algorithm to optimally select a vaccine distribution chain for a given geography and demand profile. Its output, based on analysis of the underlying transport system, takes as input a mission target with respect to population coverage in a given time frame, and selects an optimal pattern of distribution centres, along with transport frequencies and equipment to store inventory at facilities, to deliver a two-tier logistics system at least cost according to a given set of simplified transport models and logistical constraints. Recent application in Bangladesh demonstrates the effectiveness of MILES to response to national vaccination logistics plan (Gripton and Greening 2022). The self-organising tool enabled optimum location hotspot delivery hubs to distribute vaccines efficiently.

4.2. Electric road system application

Another algorithm present in the MILES environment considers the effects of an electric road system (ERS) on the range of required battery sizes for a decarbonized HGV fleet. It uses assumptions for grid power and HGV motive power to derive the likely rate of battery accumulation for HGVs when travelling along ERS enabled roads, which in turn produces a maximal battery depletion level for the journey, that can then be used to inform the size of the backup battery required for the journey. Preliminary studies demonstrated a hypothetical case study of the ‘eHighway’ overhead catenary system in Southern England with large support from the industry (de Saxe et al. 2021) and with its on-going recent development and discussion (Ainalis et al. forthcoming). Such an analysis could be included in a cold-chain analysis for a decarbonized fleet, potentially with the battery accumulation rate recalculated to take in to account the extra energy required to keep the refrigerated trailer powered. In addition, the MILES ERS model optionally includes the ability to take on a rapid charge at certain specified road locations; inclusion of this feature would allow a robust approach to cold chain planning even in remote locations, should the required static charging infrastructure be present nearby.

4.3. Electrification of home delivery groceries – last mile cold chain simulation

It has been discussed in the earlier section that some parts of the cold chain are carried out using 3.5ton vans and diesel fuelled vehicles. Therefore, one way to reduce the environmental impacts of cold chains is to replace diesel vehicles with electric. One of the obstacles in implementing electric vehicles is range anxiety. This is because electric vehicles typically have shorter range compared to diesel vehicles and require substantial time to recharge the battery. Our recent studies as reported in Utomo et al. (2019) and Utomo et al. (2021) have demonstrated how replacing diesel vans with electric vans is possible in home-grocery-delivery operation in Manchester. This was done through agent-based modelling and simulation embedded in MILES. The electric vehicles in this model have cold storage to carry chilled and frozen payloads, that is powered by electricity, which consequently reduce the (electric) vehicle’s range. However, the simulation results show that using the same fleet size, this electric vehicle fleet is able to deliver the same amount of order as diesel vehicles. Notwithstanding the promising potential, we observed the use of electric vehicle will significantly reduce the punctuality of the delivery (service level) by about 30% (Utomo et al. 2019). The simulation outputs also point out several strategies that can recover the service level without increasing the fleet size, these strategies include: (i) using fast charger; (ii) introducing opportunistic charging outside the store and closer to the customer location; and (iii) smart charging to reduce the charging time (Utomo et al. 2021).

5. Introducing CRIO to modeling framework for sustainable cold chain

Following successful works applied in MILES as discussed above, a conceptual model of cold chain has been developed to lay the ground for further simulation modelling in response to cold chain research agenda. The development of the model is pretty much informed by our previous and on-going research works. This includes the relevance of agent-based modelling in agri-food supply chain as reported in Utomo et al (2018) and food system dynamics as reported in recently completed European Union’s Horizon 2020 funded research: VALUMICS project (https://cordis.europa.eu/project/id/727243).

A multiagent-based cold chain model has been developed using Scottish salmon supply network. The conceptual model adopts the capacity, roles, interaction and organization (CRIO) meta model approach, due to its superiority of accommodating dynamic behaviour without compromising internal design (Cossentino et al 2010). Scottish salmon is the largest UK food export with around over 180k tons annual production at over 200 salmon farms and consumed in UK and exported to over 65 nations (Agriculture and Rural Economy Directorate, 2019). Please refer to Fig. 1 to refresh illustrative cold chain logistics system that then be broken down into several domain: problems, agents and solutions as illustrated in Fig. 2.

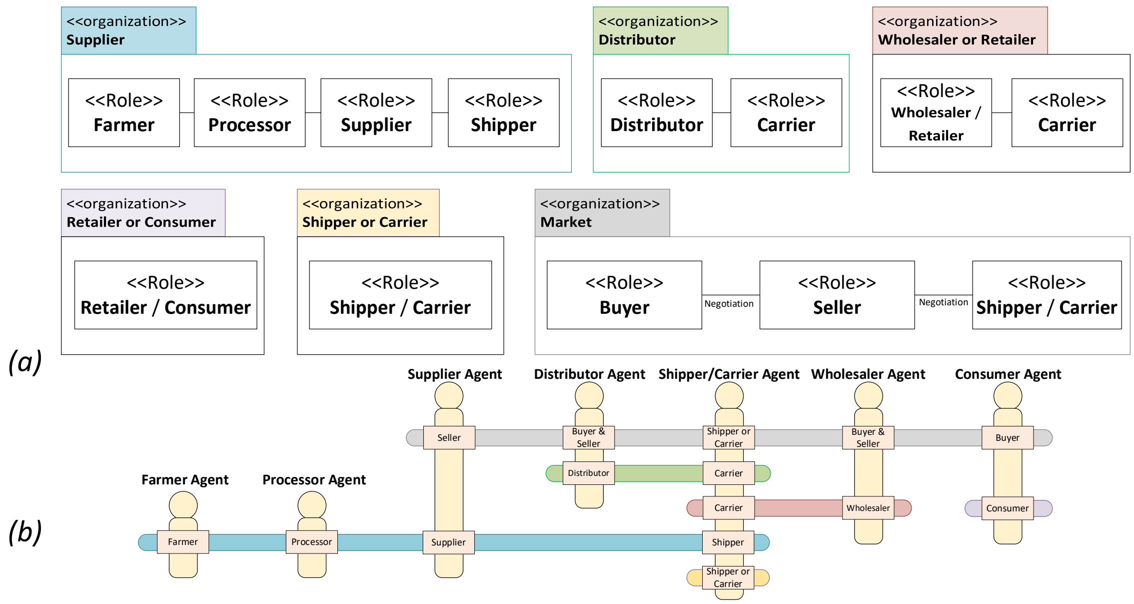

Fig. 2. Cold chain multiagent supply chain and logistics concept (Source: Hussain et al, 2022); (a) supply model assigned to six organisations and their corresponding roles; and (b) agents play role within the designated organisational groups.

5.1. Problem domain

The conceptual framework of the salmon supply model is divided into six distinct organizations, each with its own specific roles, as illustrated in Figure 2(a). It is important to note that the organisational concept allows for the formation of multiple instances or groups where various agents coordinate to achieve their mutual tasks. The organizational structure serves as a framework for coordinating the activities of a company's various agents, handling internal operations, and addressing issues that may arise. It encompasses a range of entities, such as suppliers, distributors, wholesaler, and retailers. This structure also facilitates collaboration between agents and external groups, like markets, where different agents work together to meet their buying and selling objectives. The following sections provide a concise overview of each of the six organizations employed in the simulation design.

The *Supplier Organisation* creates different supplier-groups in which the farmers (can be multiple), processors (can be more than one), supplier and the shipper agents may play their roles. If the supplier company has its own farms and processing plants, the associated farmers and processors will play their roles in that supplier-group. If the supplier company has no processing plants, the processor agent is not part of this supplier-group, and if it has no farms, the farmer is not part of it. If the supplier company has an internal shipper, the shipper agent will be member of the supplier-group. In the supplier-group, all the agent roles can collaborate to complete the supplier company's tasks.

The *Distributor Organisation* creates distributor-groups, and each group represents a distributing company. The distributor agent plays a distributor role in its distributor-group and interact with internal carrier agent to distribute the salmon sales to wholesalers or retailers. The carrier agent plays the role of a carrier in which he is receiving information about salmon delivery from the distributor agent and deliver to the wholesaler's locations.

The *Wholesaler or Retailer Organisation* creates instances (wholesaler-groups) for the wholesale or intermediate retailing companies. In wholesaler-group, the wholesaler agent will play its role to manage the sales and purchases as well as to interact with the internal carrier. The wholesaler interacts with internal carrier to assign the last-mile distribution responsibilities.

The *Retailer or Consumer Organisation* enables the final entity (by creating its instance) to represent the salmon consumption. In any case either as a retailing store or as an end customer, the salmon is provided as a final delivery. The retailer or end customer will play the consumer role in his group.

In this simulation, the *Shipper or Carrier Organisation* is used to create the instances for the external shipping or carrying companies. In each instance, the shipper or carrier agent manages drivers, cold chain logistics, internal company matters, and shipment and distribution schedules and is responsible to provide the cold chain transportation and logistical services.

The *Market Organisation* is used to create instance(s) for the negotiations where different buyers, sellers and venders can interact and negotiate to exchange products and services. This organisation is used to provide agents with access to the market, where they can communicate with external companies to buy and sell salmon and hire external shippers / carriers' services. In this organisation, the supplier agent will play the seller role only however the distributor and the wholesaler or intermediate retailing agents can play both roles: buyer and seller. The consumer agent will play the buyer role only. The shipper/carrier agent play its role to interact with suppliers and distributors to provide the vending services. If the sellers (suppliers, distributors, wholesalers) do not have internal transportation facilities, they might arrange with external shippers and carriers to transport the salmon.

5.2. Agent domain

The agent domain is dedicated to the development of an agent-oriented model that is a solution to the model of the problem domain. Agent identification, agent grouping utilising organisational concepts, agent behaviour modelling, integrating agents in a specific context, and connecting them are the steps for designing the multiagent simulation for salmon supply.

After organisational design, this model is translated into a society of agents responsible for desirable roles and behaviours. Fig. 2(b) maps organisations to agents, with agents playing roles in dedicated groups. A group is an organisational body in which members communicate based on predetermined criteria and norms. In different groups the agents are subsequently completed several tasks that are appropriate for them. The agents are expected to oversee how each role in the related group behaves. The agents' behaviour in various roles can be designed using the state transition machines. Fig. 2(b) also depicts the agents involved in several groups and described below:

Farmer, Processor, and Supplier: The farmer and processor agents are member of the supplier-group only. The supplier agent is part of both the supplier-group and the negotiation-group (in which he can negotiate with buyers for selling the processed or unprocessed salmons and can employee the external shipper).

Distributor Agent: The distributor agent oversees the distributing company in the distributor-group and can collaborate with the internal shipper agent in order to distribute the salmon. He is also member of the negotiation-group (instance of the market organisation) where he can interact with other agents (suppliers and wholesalers) to buy and sell salmon and can also hire external carrier.

Wholesaler or Intermediate Retailer: The behaviour of this agent is similar to the distributor agent. The wholesaler / intermediate retailer agent is member of the wholesaler-group as well as the negotiation-group and interact with external agents.

Consumer Agent: This agent is simply dealing with the sellers in order to purchase the salmons in the negotiation-group and consume it in the consumer-group.

Shipper or Carrier Agent: As a member of the supplier, distributor, and wholesaler groups, this agent will function as an internal shipper/carrier. It will be a member of the external shipper/carrier-group that only provides packing and shipping/carrying services. This agent will interact with the sellers as part of the negotiation-group to offer its services to transport the cold chain salmon to the buyer's sites.

6. Discussion

The objective of this paper has been to review cold chain studies, highlight the negative impact of cold chain (among many positives), and introducing the modeling framework to support research and development in addressing sustainable cold chain. The unique feature of cold chain is refrigeration system, that it is a system of linked components, including transportation. Since it is a system, we modeled a complete system, where transport (the moving component) alongside other components, precooling hubs, refrigerated warehouses, and retail/catering/domestics refrigeration (all the static components) considered not separately. The conceptual model developed in the previous section is envisaged with complexity eyes to enable interdependent interaction simulation between each component. The system can be multi-level where decisions made by different organisations influence decision by any focal organisation, in particular the location of cold chain hubs and the transportation between those hubs.

7. Conclusion

Cold chain has emerged as new research agenda supported by multiple stakeholders involving international governments, academics and industries. We have reviewed literature from various sources: academics, industries and other grey literature and concluded that cold chain technologies, such as transport refrigeration and its environmental impact has been explored but the effect to the changing response of multi-sector to climate change and sustainability is only just beginning to be discovered. This is especially true when looking at cold chain to drive infrastructure planning.

Traditional freight transportation survey and analysis have not differentiated refrigerated transport from other freight transportation, and this has indicated the relative non-significant impact of refrigerated transport among other freight. However, with the gradual transition to clean transportation, cold chain logistics and transportation impact became clearer and deserve greater attention. This is especially the case of food system which is critical component of urban economy.

An agent-based framework for cold-chain supply has been introduced in a complex setting to simulate business logic operations and model cooperation between producers, intermediate agents, and suppliers. Cooperation modelling is required to enable decision making for the cold chain in logistics and transportation perspectives. The agents are dynamic in nature and can learn from emergent behavior in a progressive and iterative manner, and the actors in the cold chain share these characteristics. The organisational concepts were used to create different groups in an environment where actors with similar goals can work together to achieve their desired outcomes. The simulation will be built around a number of innovative components, such as technology interventions and logistics strategies that will be beneficial to the environment in the long run. Initially, the simulation will be developed for the United Kingdom region by studying the actual geographical area as well as infrastructure and traffic data.

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