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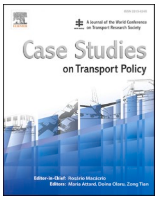

Developing a sustainable road-rail multimodal distribution network for improved animal welfare and meat quality under carbon tax in Queensland, Australia

Mahla Babagolzadeh [a], Yahua Zhang [b,*], Hang Yu [c], Jianming Yong [a], Tarryn Kille [a], Anup Shrestha [a]

[a] *School of Business, University of Southern Queensland, Toowoomba, Queensland, Australia*
[b] *UniSA Aviation, STEM Unit, University of South Australia, Adelaide, Australia*
[c] *China Institute of FTZ Supply Chain, Shanghai Maritime University, Shanghai, China*

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ABSTRACT

There have been ongoing calls for reviving the rail system in Australia to transport cattle and meat products which is thought to be more reliable transport mode than road transport. This paper aims to develop a decision support model for the road-rail network for meat and cattle transportation. This model considers animal welfare, traffic congestion, and meat quality loss due to the delay of transportation as well as the effects of a carbon tax. The proposed model generates an optimal network configuration in which each leg of the journey is conducted by the most reliable and efficient transport mode. We implement this model using the meat and cattle supply chain case of Queensland that that comprises production regions, terminals, abattoirs, seaports and distribution centers. The results indicate that the road–rail multimodal network would be preferred if animal welfare issues were prioritised. Our decision support model is expected to support policy makers in making decisions to design a transport network with optimum balance of economic and environmental goals.

1. Introduction

One of the great challenges in the sustainability of supply chains is the high energy consumption, particularly in transportation and storage (Fichtinger et al., 2015). Road transport is one of the energy intensive and, consequently, high pollution transport modes (Sörensen et al., 2012). Road transport alone accounts for 71 % of the CO_2 emissions generated by the transport sector in the European Union (UIRR, 2009). Fuel cost constitutes a significant part of the total cost in long-haul road transport (about 30 % of the total cost) (MacGowan, 2010). In recent years, traffic congestion has been a serious issue, making road freight an unsustainable transport mode (Resat and Turkay, 2019). Hence there is a need to reduce the use of road transport and increase the use of other transport modes to improve the efficiency of agricultural product supply chains. An intermodal transport network is a promising strategy to achieve this goal as it offers opportunities to reduce transport costs and to mitigate road congestion and environmental impacts (Kumar and Anbanandam, 2020; Baykasöglu and Subulan, 2016; Sörensen et al., 2012). As noted by de Miranda Pinto et al. (2018), an intermodal transport network can be less energy intensive and more sustainable than a unimodal transport network. The most common intermodal transport network is road–rail with links to seaports. This is the leading cost-effective and environmentally friendly supply chain according to de Miranda Pinto et al. (2018) who reported that intermodal road-rail operations can generate 77.4 % fewer emissions and 43.48 % more energy efficiency than the unimodal network relying on road transport only.

Public concern about animal welfare in the food transport chain is growing rapidly, particularly in relation to the livestock industry. Studies have shown that consumers are increasingly paying attention to the conditions under which their food is produced, with animal welfare being one of their main concerns (Alonso et al., 2020). When animals are transported from farms to slaughterhouses and then to retailers, their welfare can be significantly compromised, leading to increased public unease (Blokhuis et al., 2008). Consumer perceptions of animal welfare in transport can significantly influence their purchasing decisions, suggesting a deep societal interest in animal welfare (Miele et al., 2013). Although Australia has made significant strides in improving animal

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* Corresponding author.
E-mail address: shane.zhang@unisa.edu.au (Y. Zhang).

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welfare in logistics, there is still much work to be done. Uniformity and transparency continue to be at the forefront of discussions in the field (Morton and Whittaker, 2022). Ongoing issues include ensuring compliance with regulations, dealing with long-distance transport, and addressing the unique challenges posed by Australia's harsh climate.

An awareness of environmental issues in supply chains has been growing (Validi et al., 2014; Seuring, 2013; Wang et al., 2011). However, the history of carbon tax policy in Australia has been fitful and inconsistent. Australia had introduced a carbon tax policy as part of the Clean Energy Act 2011 (Australian Government, 2011). This policy, in place from 2012 to 2014, put a price on carbon emissions and was particularly influential in sectors such as logistics. This led companies to improve operational efficiencies to reduce emissions and encouraged investment in cleaner technologies (Siriwardana et al., 2011). However, this carbon tax policy was repealed in 2014 (Hanna, 2023) following a change in government. Since then, Australia's approach to reducing carbon emissions has been largely based on the Emissions Reduction Fund (Hanna, 2023), providing incentives for a range of industries to adopt new practices and technologies which reduce or limit greenhouse gas emissions.

Promoting the sustainability of supply chains needs to be supported by government policies (Sheu, 2008, 2011). Policy makers have introduced incentives and regulations to reduce emissions from supply chain operations (Mohammed et al., 2017). A carbon tax policy can be used to lead to the restructuring of the transport network from unimodal to intermodal operations to improve sustainability (Oreskes, 2011; Li et al., 2017). It has more advantages than other options from a practical perspective: it is easier to implement (Lu et al., 2010) and can be amended quickly once new information is released (Pearce, 1991).

The transport of livestock and meat products contributes significantly to CO_2 emissions in the meat supply chain (Soysal et al., 2014). Meat supply chains also face challenges to the quality of the livestock, final products and price through an increase in delivery time in road transport due to traffic congestion and a decline in the animals' welfare during transportation (Peeters et al., 2008; Gregory and Grandin, 2007). Therefore, it is important to consider animal welfare, quality of meat products and environmental impact in managing a meat supply chain. This study attempts to propose a decision support model focusing on multimodal transport network for a meat and cattle supply chain considering traffic congestion, animal welfare and the quality of meat products during transport operations under a carbon tax policy.[1] We analyse how these factors can affect transport mode selection decisions using a case in Queensland which involves cattle and associated meat products being sent to the Brisbane seaport for export. The results obtained from the case study can help decision makers to design a transport network appropriate for achieving economic and environmental goals.

2. Literature review

An efficient transport network is crucial for a country or region to attract tourists, investment and increased international trade (Zhu et al., 2019b; Kumar and Anbanandam, 2020). As reported by Buhler and Jochem (2008) and Kumar and Anbanandam (2020) intermodal transport is one of the strategies with promise to achieve this goal. An intermodal transport network uses a combination of different transport modes such as rail, road and maritime to distribute products along supply chains (Abbassi et al., 2018). There has been a wide range of applications for intermodal transport networks, including the import/export of freight (Baykasŏglu and Subulan, 2016), the shipment of hazardous material (Assadipour et al., 2016) and passenger movement (Kang et al., 2015; Zhu et al., 2019a). Mathisen and Hanssen (2014) give a good survey of the development of intermodal transport networks.

In Arnold et al. (2004), an integer linear model was used to find the best location for rail-road terminals for freight transport. Limbourg and Jourquin (2009) presented a heuristics model based on a P-median problem and the multimodal assignment problem to solve the intermodal hub location problem in Europe. Ishfaq and Sox (2011) developed a hub location model based on a P-hub median approach to design a road-rail intermodal network that accounts for model connectivity costs and service time requirement. Abbassi et al. (2019) built a robust optimisation model for a road-maritime intermodal network to capture the uncertainty of terminals' capacities and transport costs.

As CO_2 emissions from transport networks are one of the main contributors to climate change (), some researchers incorporate environmental impacts into their intermodal transport network models. Bauer et al. (2010) proposed an integer linear programming model to address the environmental impacts in intermodal transport networks and used the case of a rail network in Eastern Europe to evaluate their model. Qu et al. (2016) presented a model to explore the effect of environmental considerations and intermodal transfers on an intermodal network design. Their results show that the proposed intermodal transport network provides a better performance than the unimodal network. Demir et al. (2016) developed a stochastic optimisation model for a green intermodal transport network in the presence of uncertainty. They used a sample average approximation method to capture the uncertainty related to travel time and demand. The results indicate that demand uncertainty has less impact on the optimal solution than travel time uncertainty.

Baykasŏglu and Subulan (2016) presented an optimisation model to address transport mode selection, out- sourcing and load allocation decisions in the international intermodal road-maritime-rail network in Turkey. The main focus of the model was to determine the optimal import and export load flow with an aim of minimising costs, transit time and environmental impact. However, these studies incorporated environmental impacts into intermodal network design without considering the design of a proper carbon policy. Hoen et al. (2014) focused on the effect of carbon emissions policies on transport mode selection decisions with demand uncertainties. They demonstrate that even though considerable carbon emissions reduction can be gained by shifting to a different mode, the final decisions are subject to nonmonetary and policy considerations. Wang et al. (2015) presented a two-stage Stackelberg gaming model to analyse the effect of carbon taxes on transport mode selection and social welfare. Their results illustrate that social welfare improvement by imposing carbon taxes is dependent on the social cost and the tax rates.

Traffic congestion not only leads to a longer delivery time and the associated customer dissatisfaction, but it also contributes to higher energy consumption and environmental pollution (Resat and Turkay, 2019). Thus, it is important to consider traffic congestions in studying transport mode selection problems. Parola and Sciomachen (2005) developed a simulation model to examine the impact of traffic growth at a seaport on the land infrastructure and to determine the level of congestion at the truck gates and the degree of saturation of railway lines. Mishra and Welch (2012) presented a model using vehicle emission pricing as an emissions reduction strategy in the intermodal transport network. The results show that the emissions level depends on traffic conditions. Burgholzer et al. (2013) presented a model to analyse the impact of disruptions in intermodal transport networks by using a traffic micro simulations. Resat and Turkay (2015) used a mixed integer linear model and accounted for time-dependent traffic congestion constraints to design a reliable road-maritime-rail intermodal network to decrease traffic congestion and increase transport safety. They used an *E-constraints* method to solve the model with a case of the Marmara region in Turkey.

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[1] Much of the literature reviewed in this study uses the term 'intermodal'. However, Multimodal might be more appropriate as pointed out by one referee, because when dealing with cattle transportation, the intermodal transport units are not used. The two terms are used interchangeably and refer to the same meaning in this paper.

Lin and Chen (2017) used a simulation-based multimodal traffic assignment model to estimate the traffic volumes due to a planned special event. Kelle et al. (2019) presented a simulation model accounting for traffic congestion to explore the benefit of mode changes and to evaluate the trade-off between environmental objectives and other performance indicators such as reliability. They concluded that better environmental performance would be achieved by switching freight from road to rail transport and that this switch would also mitigate road congestion. Resat and Turkay (2019) proposed a bi-objective optimisation model accounting for time-window and traffic congestion constraints to analyse the cost and environmental impact of the intermodal transport network. The results demonstrate the importance role of the ports, railway stations and transhipment centers in helping companies to make their additional investment decisions.

As different transport modes lead to different delivery times which can have different impacts on the quality of products, there is a need to consider a quality measurement in the intermodal transport problem in food supply chains to avoid additional costs. Soysal et al. (2014) presented a linear programming model for a multimodal beef supply chain in Brazil to minimise both emissions and transport costs. However, they do not address the loss of quality during the transport process. A bi-objective optimisation model was proposed by Abbassi et al. (2018) to control for both total costs and delivery time in an intermodal transport network for agriculture products. They addressed the problem of quality loss during transport operations by considering a constraint that does not allow total transport time to exceed the lifetime of the product.

Research into animal welfare during livestock transport has focussed on themes including: the physiological and psychological stresses on livestock; the impact of loading density; and the effects of long-distance transport. One area of particular interest was the stress faced by livestock during transport. An example of such research is the study by Cockram et al. (1996), where the physiological responses of sheep during road transportation were evaluated. The study investigated spacing and length of travel and found that during transport, sheep exhibited signs of both physical and psychological stress, including increased cortisol levels and heart rates. Santurtun and Phillips (2015) conducted a review of literature on the impact of vehicle motion during transport on animal welfare. The research argued that studies conducted on road transportation effects in domestic animals showed several motion sickness behaviours including vomiting and a reduction in rumination. The study highlighted that motion plays a welfare role during animal road transport, producing motion sickness and stress responses in transported livestock.

Another important area of research has been the impact of loading density on farm animal welfare during transport. A study by Fisher et al. (2010) discovered a link between loading density and animal welfare during transport, particularly in relation to heat stress in cattle. Schwartzkopf-Genswein et al. (2012) discovered that loading density during road transport had a significant impact on animal welfare (stress, health, injury, fatigue, dehydration, core body temperature, mortality and morbidity) and carcass and meat quality. Schuetze et al. (2017) conducted a review of literature focused on the topic of current industry practices of land transport of finished cattle, primarily within the United States and Canada. The authors found that loading density and duration of transport affect animal health and carcass quality.

The effect of long-distance transport on animal welfare has also been investigated. A study by Petherick (2005) investigated the impacts of transport duration on cattle welfare, finding that long duration transport was associated with a higher incidence of stress and injury. Later, Petherick and Phillips (2009) argued that that the amount of space provided to animals governs important elements of their behaviour hence it is critical to their health and welfare. Nielsen et al. (2011) suggest that although animal transport of long duration is more likely to compromise animal welfare than journeys of shorter duration, it is crucial to acknowledge that it is not journey duration alone, but the associated negative aspects that are the cause of the observed welfare issues. Factors such as extreme temperatures and lack of food, water and rest are all exacerbated by the length of exposure, and thus, journey duration. This has implications for domestic transport within Australia, where distances can be vast.

Cattle production has been considered one of the largest sources of greenhouse gas emissions (Chen et al., 2020). In addition to the methane produced by cattle, the use of transport within agricultural practices and logistics is also inextricably bound to cattle production. Thus, accounting for transportation is an important part of the life cycle analysis of beef cattle production as it is associated with energy consumption and greenhouse gas emissions (O'Mara, 2011). Almost all beef cattle are transported more than once. For example, feeder calves might be transported from a ranch to a livestock auction market, order-buying station, backgrounding facility, pasture as a stocker, feedlot, and finally to a beef processing facility. Under the above assumptions, the calf could be transported six times during its life (Kannan et al., 2016).

Research has highlighted the potential for a carbon tax to promote a shift from road to rail transport. Some authors have suggested that a carbon tax could make rail transport more financially attractive for freight transport, given its lower emissions per ton-kilometer relative to road transport (Webber, 2018; PIERCE, 2020; Li and Zhang, 2020). Thus, suggesting that a carbon tax could potentially reshape freight transport network selection in Australia's livestock industry. However, Fahimnia et al. (2013) investigated the impact of carbon pricing in Australian logistics. Their study argues that the current carbon-pricing scheme in Australia may only make a minor increase in the overall logistics costs that may be inadequate to drive a significant shift in transport behaviors (Fahimnia et al., 2013).

From the above literature review, it has been clear that there is a need to develop a comprehensive decision tool considering animal welfare, quality of meat products and environmental impact simultaneously. This is lacking in the existing literature. This paper aims to fill this gap.

3. Problem description

Agricultural production in Queensland, Australia is scattered widely in an area of 1.85 million km^2. Livestock travels long distances from remote locations to slaughtering and processing facilities near large cities and then to the Port of Brisbane for export (Woodhead et al., 2016). Rail was the main mode of long- haul transport in Queensland previously, but in the past decade the use of rail declined and road transport has become the dominant mode for long-distance transportation. This is because trucks have the advantage of providing a more flexible service in terms of scheduling, route and size of load (Woodhead et al., 2016). With the roads becoming increasingly congested, the Queensland government has expressed an intention to expand the share of transport by rail by reviving the Queensland Western Rail System, thereby increasing regional connectivity and freight market access.

In this research, we develop a decision support model for a rail-road intermodal network for managing the meat supply chain with considerations for animal welfare and traffic congestion constraints under a carbon tax policy. Our research focuses on a multi echelon supply chain that comprises production regions, terminals, abattoirs, seaports and distribution centers as destination points. Cattle are transported from production regions to abattoirs for slaughtering or directly to the seaports for livestock exporting. After slaughtering and processing, meat products are transported to the seaports for exporting or to distribution centers for domestic consumption. Two transport modes – road and rail – are used for carrying cattle from the production regions to the abattoirs or seaports and for distributing meat products from abattoirs to the seaports or distribution centers. Terminals are multimodal network nodes that link the road and rail networks, and animals and meat products are offloaded and uploaded here.

We assume 40-foot cattle containers are used for transporting the cattle from the production regions to the abattoirs and seaports.

Transporting the meat products between the abattoirs and the final destinations (seaports and distribution centers) uses 40-foot normal containers. A vehicle is used to carry each container. In the multimodal network, when trailers used for transferring containers arrive at terminal points the containers will be directly transferred from the trailers to trains. The capacity of a train is assumed to be C^t containers. A transit time T is assumed at each terminal for changing from one transport mode to the other. Transporting animals can have an impact on the animals' welfare and, consequently, on the quality of the meat products, so we consider an animal welfare reduction coefficient for each transport mode.

The proposed model incorporates carbon emissions from the operations of the different transport modes. We consider a threshold for meat products distributed from the abattoir to the seaport or distribution center. Hence, the quality loss is assumed if meat products arrive at a destination point later than the expected threshold. The transport cost comprises two components – the fixed cost when a transport mode is used and the variable cost. The following assumptions are applied in formulating the proposed problem:

- 4. Demand at the final destinations is assumed to be constant and known in advance.
- 5. Each destination node can be visited by only one vehicle and there is no split delivery.
- 6. There is a threshold (T^s) for shipping meat products from the abattoir to the final destination node considering the meat's shelf life. Hence, quality loss (π) is assumed if meat products arrive at the destination point later than the expected threshold.
- 7. Shortage is not allowed.
- 8. 40-foot cattle container and 40-foot normal containers are used for cattle and meat products transports, respectively, in either the unimodal or multimodal network.
- 9. A train with a maximum capacity of C^r containers is used for transporting cattle and meat products between terminals in the multimodal network.
- 10. We assume a constant speed for the train, while different speeds are considered for vehicles because of the traffic congestion of roads.

The decision support model seeks to select an effective transport mode and to determine the quantity of cattle and meat products to be shipped through the unimodal and multimodal network to minimise transport costs, quality loss costs, animal welfare reduction costs and emissions costs. A decision support system model for optimized transport mode in meat supply chain is illustrated in Fig. 1.

4. Mathematical model

This section presents the mixed linear programming model. The objective function aims to minimise transport costs, quality loss costs, animal welfare reduction costs and emissions costs. We examine the opportunities of expanding the use of rail to ship cattle and meat products to the Brisbane seaport for export and to distribution centers in Brisbane for domestic consumption.

The model considers traffic congestion for road transport and its impact on fuel and emissions costs. We utilise the same approach as Resat and Turkay (2019) and Franceschetti et al. (2013) to simulate traffic congestion in the proposed model. Following these studies, we divide the planning horizon into three time intervals – free flow ($m = 1$), a transient period which is a mixture of free flow and congestion ($m = 2$) and traffic congestion ($m = 3$). We assume vehicles start their travel at the maximum speed which is usually equal to speed limit roads in the free flow interval, lasting a unit of time ζ, followed by a period of congestion where vehicles travel with lower speed level.

The proposed multimodal problem can be defined as a graph $G = (V, A)$, with V being the set of nodes and A the set of arcs. In V, N_F is the set of production regions, N_T the set of terminals, N_A the set of abattoirs, N_{DC}

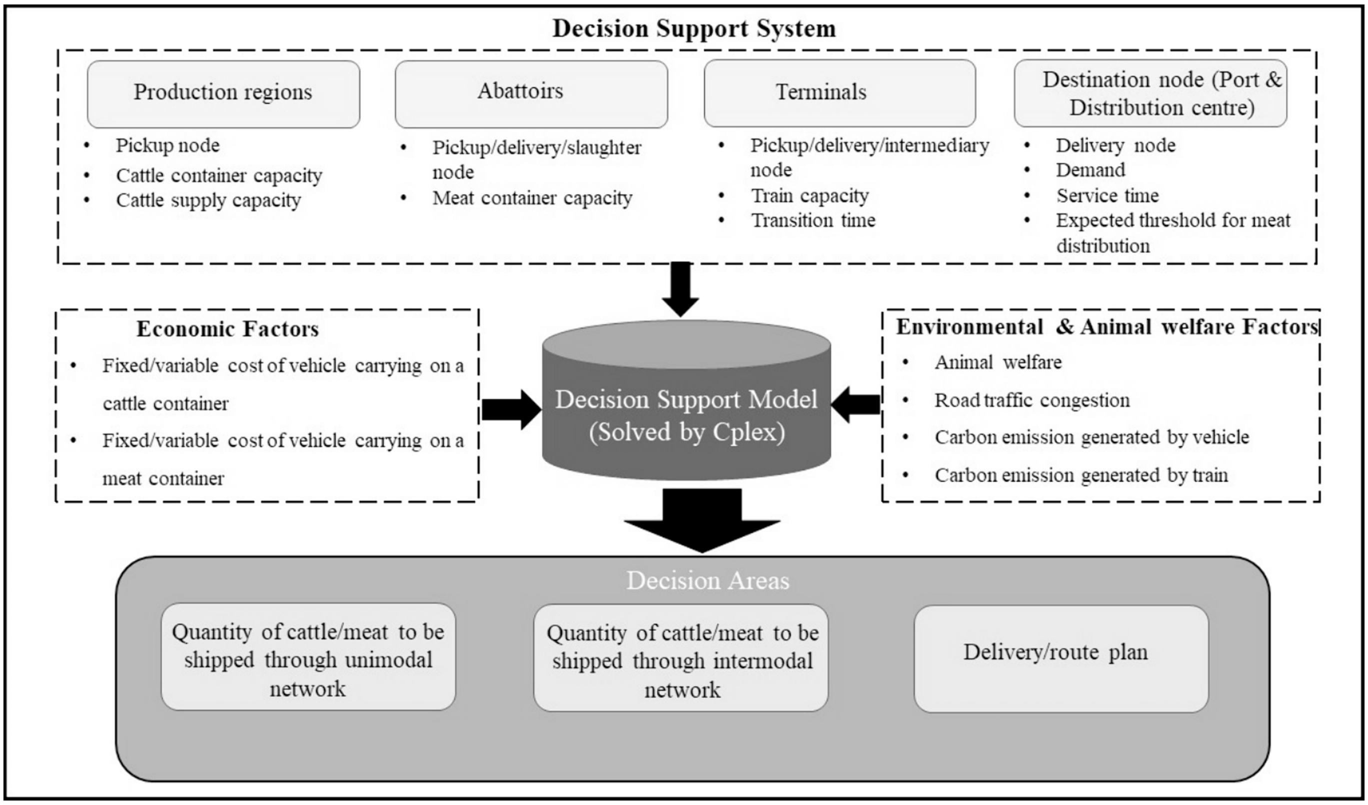

Fig. 1. A decision support system model in meat supply chain.

the set of distribution centers and N_P the set of seaports $-$ $V = N_F \cup N_T \cup N_A \cup N_{DC} \cup N_P$. The arc set A represents the links available between the nodes. The cattle and meat products can be shipped through either the unimodal or multimodal network using terminals from the production regions to the abattoirs/seaports or from the abattoirs to the distribution centers/seaports. We consider N_S as total number of nodes and $(N_S + 1)$ as a dummy point. With no loss of generality, it is assumed that there are unlimited containers and trailers for distribution in the meat supply chain.

The notations are presented in Table 1, 2 and 3 with the Greek upper cases representing the parameters, and lower cases the variables.

A mathematical formulation for the proposed problem is:

$$minz = TC + QC + WC + EC \tag{1}$$

Expression (1) is the objective function including four cost components: transport costs (TC), quality loss costs (QC), animal welfare reduction costs (WC) and emissions costs (EC). They are defined below:

Transport costs.

Transport costs (TC) are defined as follows:

$$TC = FC^v + FC^t + VC^v + VC^t \tag{2}$$

The Transport costs (TC) include the fixed costs of vehicles (FC^v), fixed costs of the train (FC^t), fuel costs of vehicles (VC^v) and fuel costs of the train (VC^t). These costs are formulated as follows:

$$\begin{aligned} FC^v = & \sum_k \Bigg(\sum_{i \in N_F} \sum_{j \in \mathscr{V} \backslash N_F, i \neq j} F^c x_{ijk} + \sum_{i \in N_T} \sum_{j \in N_A \cup N_P, i \neq j} F^c x_{ijk} \\ & + \sum_{i \in N_A} \sum_{j \in N_T \cup N_{DC} \cup N_P} F^p x'_{ijk} + \sum_{i \in N_T} \sum_{j \in N_{DC} \cup N_P} F^p x'_{ijk} \Bigg) \end{aligned} \tag{3}$$

The first two parts of function (3) represent the fixed costs related to the vehicles carrying on cattle containers and the remaining parts compute the fixed costs of using vehicles carrying on normal containers.

The fixed costs of using trains are presented by function (4).

$$FC^t = \sum_k \sum_{i \in N_T} \sum_{j \in N_T, i \neq j} F^t \left(x_{ijk} + x'_{ijk} \right) \tag{4}$$

Following Bektaş and Laporte (2011) and Franceschetti et al. (2013), we calculate the fuel consumption of vehicles as a function of load and travel speed. The fuel costs of vehicles are formulated as follows:

$$VC^v = P^f V^v \tag{5}$$

Function (5) represents the fuel costs of vehicles in which V^v refers to the fuel consumption of vehicles. It comprises three components: the *enginemodule* (linear with the time travelled); the *speedmodule* (quadratic in vehicle speed); the *weightmodule* (not related to the vehicle speed and travel time). The fuel consumption is defined as follows:

$$V^v = \sum_k \sum_i \sum_j \sum_m \lambda \phi \left(\theta_{ijm} \left(w_{ijkm} + w'_{ijkm} \right) + \eta_{ijm} \left(s_{ijkm} + s'_{ijkm} \right) \right) + \tag{5.i}$$

$$\sum_k \sum_i \sum_j \sum_{m=1,3} \lambda \Gamma (S_m)^3 \left(\theta_{ijm} \left(w_{ijkm} + w'_{ijkm} \right) + \eta_{ijm} \left(s_{ijkm} + s'_{ijkm} \right) \right) + \tag{5.ii}$$

Table 1
The sets and indices for the mathematical formula.

i, j, n	Index of nodes including production regions, terminals, abattoirs, destination points,
$i, j, n \in V \cup \{(Ns + 1)\}$	
κ, l	Index of containers

Table 2
The parameters for the mathematical formula.

W^c	Average carcass weight of a cattle *(kg)*
W	Average cattle weight *(kg)*
D_{ij}	The distance from node *i* to *j*
D_{mi}	Demand for meat at destination point *i*
Dl_i	Demand for cattle at seaport *i*
C^t	Capacity of train in container
C^c	Capacity of a cattle container (head of cattle)
C^n	Capacity of a normal containers used for shipping meat products (*ton*)
S^t	Train speed
S_m	Vehicle speed in time interval *m*
T	Transit time at terminals for changing the transport mode
St_i	Service time at node *i*
T^s	Expected threshold for distribution of meat products
B_{ijm}	Time at which the time interval changes to *(m + 1)*
θ_{ijm}	Technical parameter to calculate travel time
η_{ijm}	Travel time from node *i* to *j* at time interval *m*
δ	Carbon price (*AUD/kg*)
π	Unit penalty cost if there is a delay in meat products distribution resulting in quality loss (AUD/kg)
υ^t	Animal welfare reduction coefficient per *km* by train (*head/km*)
υ^v	Animal welfare reduction coefficient per *km* by vehicle (*head/km*)
Cap_i	Cattle supply capacity of a production region *i*
σ	*CO_2* emitted by unit fuel consumption (*kg/L*)
F^c	Fixed cost of a vehicle carrying on a cattle container
F^p	Fixed cost of a vehicle carrying on a normal container
F^t	Fixed cost of train
U^t	Fuel consumption rate of train per *km* with a unit of load
P^f	Fuel price
λ	Technical parameter to calculate vehicles fuel consumption
γ	Technical parameter to calculate vehicles fuel consumption
β	Technical parameter to calculate vehicles fuel consumption
μ	Curb-weight *(kg)*
N^e	Engine speed *(rev/s)*
Φ	Engine friction factor *(kJ/rev/l)*
ι	Engine displacement *(l)*
ζ	Time at which the transient period is finished
M	A large number

Table 3
Variables.

x_{ijk}	1 If vehicle *k* is used for cattle transport on arc *(i,j)*; otherwise 0
x'_{ijk}	1 If vehicle *k* is used for meat transport on arc *(i,j)*; otherwise 0
y_{ik}	1 If cattle are transferred from production region *i* to the corresponding terminal using vehicle *k*; otherwise 0
y'_{ik}	1 If cattle are shipped through the unimodal network from production region *i* to abattoirs/seaport using vehicle k; otherwise 0
z_{ik}	1 If meat products are transferred from abattoir region *i* to the corresponding terminal using vehicle *k*; otherwise 0
z'_{ik}	1 If meat products are shipped through the unimodal network from abattoir region *i* to destination nodes using vehicle *k*; otherwise 0
f_{ijk}	Quantity of cattle (head) transported on arc *(i,j)* using vehicle *k*
f'_{ijk}	Quantity of meat products (kg) transported on arc *(i,j)* using vehicle *k*
s_{ijkm}	1 If cattle trailer k departs node *i* toward node *j* in time interval *m*; otherwise 0
s'_{ijkm}	1 If normal trailer k departs node *i* to *j* in time interval *m*; otherwise 0
u_j	Starting time of train carrying cattle trailers from terminal *j*
u'_j	Starting time of train carrying normal trailers from terminal *j*
t_{jk}	Arrival time of cattle trailer *k* at node *j*
t'_{jk}	Arrival time of normal trailer *k* at node *j*
w_{ijkm}	Starting time of cattle trailer k on arc *(i,j)* in time module *m*
w'_{ijkm}	Starting time of normal trailer k on arc *(i,j)* in time module *m*
lq_j	Delay time at destination node j

$$\sum_k\sum_i\sum_j \lambda\,\Gamma(S_2)^3\left(\zeta\left(s_{ijk2}+s'_{ijk2}\right)-w_{ijk2}-w'_{ijk2}\right)+ \tag{5.iii}$$

$$\begin{aligned}&\sum_k\sum_i\sum_j \lambda\,\Gamma(S_3)^3\left(w_{ijk2}+w'_{ijk2}+\theta_{ij2}\left(w_{ijk2}+w'_{ijk2}\right)+\eta_{ij2}\left(s_{ijk2}\right.\right.\\&\quad\left.\left.+s'_{ijk2}\right)-\zeta\left(s_{ijk2}+s'_{ijk2}\right)\right)+\end{aligned} \tag{5.iv}$$

$$\sum_k\sum_i\sum_j \lambda\gamma\alpha D_{ij}\left(\mu\left(x_{ijk}+x'_{ijk}\right)+f_{ijk}W+f'_{ijk}\right) \tag{5.v}$$

Where $\phi = \Phi N^e\iota$, $\Gamma = \gamma\beta$, $\lambda = \tau/\varphi\psi, \gamma = 1/(1000\chi\omega)$, $= gsin\theta + gC^e cos\theta$ and $\beta = 0.5C^d\rho A$ which are taken from Franceschetti et al. (2013). Function (5.i) calculates the fuel consumption generated by *enginemodule*. Functions (5.ii)-(5.iv) compute the fuel consumption generated by the *speedmodule*. The fuel consumption related to the *speedmodule* in all congestion and free flow intervals is presented by function (5.ii), while functions (5.iii) and (5.iv) compute the fuel consumption generated by the *speedmodule* in the transient interval. Fuel consumption is linked to the vehicles' load by the *weightmodule* in function (5.v). The fuel consumption of the trains is represented by function (6).

$$VC^t = P^f\sum_k\sum_{i\in N_T}\sum_{j\in N_T} D_{ij}U^t\left(Wf_{ijk}+f'_{ijk}\right) \tag{6}$$

Quality loss cost.

Quality lose costs (QC) are considered in the proposed model when a threshold considered for meat distribution is violated, and are modelled as follows:

$$QC = \pi\sum_{j\in N_{DC}\cup N_P} lq_jDm_j \tag{7}$$

The distribution of meat products must be completed before a threshold is reached. A penalty applies as a result of quality loss of meat products if the products are distributed to their final destinations later than the expected threshold. The quality loss cost is computed at each final destination by constraint set (52) (see below).

Animal welfare reduction costs.

Animal welfare reduction costs (WC) comprise the animal welfare reduction cost during the road and rail transport, and are defined as follows:

$$\begin{aligned}WC = &\sum_{i\in N_F\cup N_T\cup N_P}\sum_{j\in N_A\cup N_P, i\neq j}\sum_k f_{ijk}D_{ij}\vartheta^v+\sum_{i\in N_F}\sum_{j\in N_T}\sum_k f_{ijk}D_{ij}\vartheta^v\\&+\sum_{i\in N_T}\sum_{j\in N_T, i\neq j}\sum_k f_{ijk}D_{ij}\vartheta^t\end{aligned} \tag{8}$$

As we are focusing on cattle transport as a part of the proposed supply chain, we consider animal welfare reduction cost due to the negative impact of travel time on animal welfare which has a direct impact on the quality of the meat products. Parts 1 and 2 in function (8) are the animal welfare reduction cost incurred by road transport and the last part computes it for transport by rail.

Carbon emission costs.

Carbon emissions costs (EC) arise from the road and rail transports, which are calculated by multiplying the amount of energy consumption during transportation by the carbon emissions coefficients and the carbon price.

$$EC = \delta\sigma\left(V^v+\sum_k\sum_{i\in N_T}\sum_{j\in N_T} U^tD_{ij}\left(Wf_{ijk}+f'_{ijk}\right)\right) \tag{9}$$

The first part in function (9) computes the emission cost induced by road transport and the second part computes it for transport by rail.

The constraints of the proposed model are shown below:

S.t.

$$\sum_{j\in N_T} x_{ijk} = y_{ik}\forall i\in N_F, k \tag{10}$$

$$\sum_{i\in N_F}\sum_{j\in N_T} x_{ijk} = \sum_{i\in N_F} y_{ik}\forall k \tag{11}$$

$$\sum_{i\in N_T}\sum_{j\in N_T} x_{ijk} \leq C^t\forall k \tag{12}$$

$$\sum_{j\in N_A\cup N_P} x_{ijk} = y'_{ik}\forall i\in N_F, k \tag{13}$$

$$\sum_{i\in N_F}\left(y'_{ik}+y_{ik}\right) \leq 1\forall k \tag{14}$$

$$\sum_{j\in N_T} x'_{ijk} = z_{ik}\forall i\in N_A, k \tag{15}$$

$$\sum_{i\in N_A}\sum_{j\in N_T} x'_{ijk} = \sum_{i\in N_A} z_{ik}\forall k \tag{16}$$

$$\sum_{i\in N_T}\sum_{j\in N_T} x'_{ijk} \leq C^t\forall k \tag{17}$$

$$\sum_{j\in N_{DC}\cup N_P} x'_{ijk} = z'_{ik}\forall i\in N_A, k \tag{18}$$

$$\sum_{i\in N_F\cup T}\sum_{j\in N_P}\left(x_{ijk}+\sum_{i\in N_A} z_{ik}+\sum_{i\in N_A} z'_{ik}\right) \leq 1\forall k \tag{19}$$

$$\sum_{i\in N_F\cup N_P, i\neq j} x_{ijk} - \sum_{j\in N_P\cup\{N_S+1\}, i\neq j} x_{jik} = 0\forall j\in N_P, \forall k \tag{20}$$

$$\sum_{i\in N_T\cup N_A\cup N_{DC}\cup N_P, i\neq j} x'_{ijk} - \sum_{i\in N_{DC}\cup N_P\cup\{N_S+1\}, i\neq j} x'_{jik} = 0\forall j\in N_P, \forall k \tag{21}$$

$$\sum_{i\in N_T\cup N_A\cup N_{DC}\cup N_P, i\neq j} x'_{ijk} - \sum_{i\in N_{DC}\cup N_P\cup\{N_S+1\}, i\neq j} x'_{jik} = 0\forall j\in N_{DC}, k \tag{22}$$

$$\sum_{j\in N_T\cup N_A\cup N_P}\sum_k f_{ijk} = Cap_i\forall i\in N_F \tag{23}$$

$$f_{ijk} \leq C^c x_{ijk}\forall i\in N_F\cup N_T, \forall j\in V\Big/\{N_{DC}\}, k \tag{24}$$

$$f'_{ijk} \leq C^n x'_{ijk}\forall i\in V\Big/\{N_F\}, \forall j\in V\Big/\{N_F\}\cup\{N_S+1\}, k \tag{25}$$

$$\sum_{i\in N_F\cup N_T, i\neq j} f_{ijk} - \sum_{i\in N_T\cup N_A\cup N_P, i\neq j} f_{jik} = 0 j\in N_T, k \tag{26}$$

$$\sum_{i\in N_A\cup N_T, i\neq j} f'_{ijk} - \sum_{i\in N_{DC}\cup N_T\cup N_P, i\neq j} f'_{jik} = 0\forall j\in N_T, k \tag{27}$$

$$\sum_{i\in N_T\cup N_{DC}\cup N_P}\sum_k f'_{jik} = W^c\sum_{i\in N_F\cup N_T}\sum_k f_{ijk}\forall j\in N_A \tag{28}$$

$$\sum_{i\in N_T\cup N_A\cup N_{DC}\cup N_P, i\neq j}\sum_k f'_{ijk} - \sum_{i\in N_{DC}\cup N_P\cup\{N_S+1\}, i\neq j}\sum_k f'_{jik} = Dm_j\forall j\in N_{DC}, k \tag{29}$$

$$\sum_{i\in N_T\cup N_A\cup N_{DC}\cup N_P, i\neq j}\sum_k f'_{ijk} - \sum_{i\in N_{DC}\cup N_P\cup\{N_S+1\}, i\neq j}\sum_k f'_{jik} = Dm_j\forall j\in N_P, k \tag{30}$$

$$\sum_{i\in N_F\cup N_T}\sum_k f_{ijk} - \sum_{i\in N_P\cup\{N_S+1\}}\sum_k f_{jik} = Dl_j\forall j\in N_P, k \tag{31}$$

$$\sum_k\sum_{i\in V}\left(f'_{i\{N_S+1\}k}+f_{i\{N_S+1\}k}\right) = 0 \tag{32}$$

$$\sum_{m} s_{ijkm} = x_{ijk} \forall i \in N_F \cup N_T \cup N_P, j \in N_T \cup N_A \cup N_P, i \neq j, \forall k \tag{33}$$

$$\sum_{m} s'_{ijkm} = x'_{ijk} \forall i \in \frac{V}{\{N_F\}j} \in N_T \cup N_{DCV} \cup N_P \cup \{N_S + 1\} i \neq j, \forall k \tag{34}$$

$$s_{ijkm} B_{ijm-1} - M(1 - s_{ijkm}) \leq t_{ik} + St_i \leq s_{ijkm} B_{ijm} + M(1 - s_{ijkm}) \forall i \in N_F \cup N_T \cup N_P,$$

$$j \in N_T \cup N_A \cup N_P, \forall k, m \tag{35}$$

$$s'_{ijkm} B_{ijm-1} - M\left(1 - s'_{ijkm}\right) \leq t'_{ik} + St_i \leq s'_{ijkm} B_{ijm} + M\left(1 - s'_{ijkm}\right) \forall i \in V \Big/ \{N_F\}$$

$$j \in V \cup \{N_S + 1\} / \{N_F \cup N_A\},$$

$$\forall k, m \tag{36}$$

$$t_{jk} \geq t_{ik} + St_i - M(1 - x_{ijk}) \forall i \in N_F \cup N_T \cup N_P$$

$$j \in N_T \cup N_A \cup N_P, i \neq j, \forall k \tag{37}$$

$$t'_{jk} \geq t'_{ik} + St_i - M\left(1 - x'_{ijk}\right) \forall i \in V \Big/ \{N_F\}$$

$$j \in V / \{N_F \cup N_A\}, i \neq j, \forall k \tag{38}$$

$$t_{jk} \geq (\theta_{ijm} + 1) t_{ik} + St_i + \eta_{ijm} s_{ijkm} - M(1 - s_{ijkm}) \forall i \in N_F \cup N_T \cup N_P$$

$$j \in N_T \cup N_A \cup N_P \cup \{N_S + 1\},$$

$$\forall k, m \tag{39}$$

$$t'_{jk} \geq (\theta_{ijm} + 1) t'_{ik} + St_i + \eta_{ijm} s'_{ijkm} - M\left(1 - s'_{ijkm}\right) \forall i \in V \Big/ \{N_F\}$$

$$j \in N_T \cup N_P \cup N_{DC} \cup \{N_S + 1\},$$

$$\forall k, m \tag{40}$$

$$u_j \geq t_{jk} + T - M\left(1 - \sum_{i \in F} x_{ijk}\right) j \in N_T, k \tag{41}$$

$$u'_j \geq t'_{jk} + T - M\left(1 - \sum_{i \in A} x'_{ijk}\right) j \in N_T, k \tag{42}$$

$$t_{jk} \geq u_i + D_{ij} / S^t - M(1 - x_{ijk}) i \in N_T, j \in N_T, i \neq j, \forall k \tag{43}$$

$$t'_{jk} \geq u'_i + D_{ij} \Big/ S^t - M\left(1 - x'_{ijk}\right) i \in N_T, j \in N_T, i \neq j, \forall k \tag{44}$$

$$t_{jk} \leq M \sum_{i \in N_F \cup N_T \cup N_P} x_{ijk} \forall j \in N_A \cup N_T \cup N_P, \forall k \tag{45}$$

$$t'_{jk} \leq M \sum_{i \in V / \{N_F\}} x'_{jik} \forall j \in V \Bigg/ \{N_F\}, \forall k \tag{46}$$

$$t'_{jk} \geq t_{jl} - M\left(1 - \sum_{i \in N_T \cup N_P \cup N_{DC}} x'_{jik}\right) \forall j \in N_A, k, l \in K \tag{47}$$

$$w_{ijkm} \geq t_{ik} + St_i - M(1 - s_{ijkm}) i \in V / \{N_A \cup N_{DC}\},$$

$$j \in N_T \cup N_A \cup N_p, i \neq j, \forall k, m \tag{48}$$

$$w'_{ijkm} \geq t'_{ik} + St_i - M\left(1 - s'_{ijkm}\right) i \in V \Big/ \{N_F\},$$

$$j \in N_T \cup N_{DC} \cup N_P, i \neq j, \forall k, m \tag{49}$$

$$lq_j \geq \left(t'_{jk} - t'_{ik} - St_i - T^s\right) - M\left(1 - \sum_{l \in V / \{N_F \cup N_A\}} x'_{ilk}\right) i \in N_A, j$$

$$\in N_P \cup N_{DC}, \forall k \tag{50}$$

$$x'_{ijk}, s'_{ijkm}, x_{ijk}, s_{ijkm}, y_{ik}, y'_{ik}, z_{ik}, z'_{ik} \in \{0, 1\} \forall i, j, k, m \tag{51}$$

$$f_{ijk}, f'_{ijk}, u_j, u'_j, t_{jk}, t'_{jk}, lq_{jk}, w_{ijkm}, w'_{ijkm} \geq 0 \forall i, j, k, m \tag{52}$$

Constraints (10) and (11) ensure that multimodal link is used for cattle distribution if y_{ik} variable is non-zero. Constraint (12) satisfies the capacity limitation of train. Constraint (13) represents that unimodal link is used to distribute cattle if y'_{ik} variable is non-zero. Constraint (14) ensures that each vehicle can be used either in unimodal or multimodal links to distribute cattle from production regions. Constraints (15) and (16) denote that multimodal link is used for meat distribution from abattoirs to destination nodes if z_{ik} variable is non-zero. Constraint (17) confirms that the train capacity is satisfied when it is used for distribution of meat products. Constraint (18) indicates that the unimodal link is used for meat products distribution if there is no link from abattoir to terminal. Constraint (19) notes that each vehicle at destination points can depart from the abattoir for meat distribution or from regional production for cattle transport. Constraints (20) – (22) guarantee the connectivity on routes. The availability of number of cattle at each production region is satisfied by constraint (23).

Constraints (24) and (25) guarantee that if there is no link between two nodes, products flow is equal to zero. Constraints (26) and (27) link the product flow leaving a terminal to the product flow that entered the terminal. Constraint (28) balances cattle flow before an abattoir with meat products flow after the abattoir. Constraint (29) decreases flow of meat products on a route after visiting a distribution center by its demand. Constraints (30) and (31) ensure that the quantity of cattle/meat products entering to a seaport is equal to its demand for exporting. Constraint (32) ensures that vehicles would be empty when arriving at the dummy point. Constraints (33) and (34) ensure that each travelling on each arc *(i, j)* can be placed is at most in one time interval. The time interval at which vehicle κ travel from node *i* to node *j* is determined by (35) and (36). Constraints (37) and (38) compute the starting time of vehicle κ on arc *(i, j)*.

Constraints (39) and (40) are used to compute the arrival time at node *j* which is visited immediately after node *i* in the unimodal link due to traffic congestion at the corresponding time interval *m*. The departure time of a train is determined by (41) and (42). Constraints (43) and (44) determine the arrival time at terminal *j* which is visited immediately after terminal *i* in the multimodal link. Constraints (45) and (46) indicate that the arrival time at node *j* is equal to zero if there is no link entering the node *j*. Constraint (47) links the decision variables t'_{jk} with the decision variables t_{jl}. Constraints (48) and (49) compute the starting time of vehicle κ on arc *(i, j)*. A delay as a result of threshold violation at a meat distribution point is determined by (50). Constraints (51) and (52) denote the types of decision variables.

5. Computational results

The case study.

The need to use a multimodal network to reduce transport costs, emissions costs and animal welfare costs can be justified because of the increasing traffic congestion on roads and the negative impact of road transport on animal welfare. The case of Queensland is used to evaluate the proposed model. The case study involves a meat supply chain in Queensland, which is responsible for the distribution of cattle and meat products from production regions to destination nodes for export or domestic consumption. In this research, we examine the opportunities of expanding the use of the road–rail network in western Queensland. As the number of cattle in Queensland is more than in any other state or territory in Australia, using rail could be more efficient and reliable. In addition, the meat industry shares key roads with other sectors of Australian agriculture and so by using rail transport the meat industry may help to improve the road freight network for other agricultural sectors (Fraser, 2017).

Cattle were traditionally loaded on rail transport at two major collection points, Quilpie and Morven, in this part of Queensland. Hence, we assume these two areas as the production regions for our research. We also consider an abattoir for slaughtering and meat processing which is close to the Toowoomba region. Most of the state's cattle and meat products are exported through Brisbane. So, we use the Port of Brisbane as the destination node for the export of cattle and meat products in the proposed model. We also assume two distribution centers in Brisbane as the destination nodes for the meat products for domestic consumption. In this research, cattle and meat products can be shipped between the production regions, the abattoir and the destination nodes using either unimodal or rail–road multimodal networks. Hence, we assume three terminals near rail stations as the transfer points for the transport modes in the multimodal network. Terminal 1 is used for the distribution of cattle from the production regions to the abattoir and Brisbane seaport, terminal 2 is linked to the abattoir for the distribution of cattle and meat products and terminal 3 is used to distribute cattle and meat products to the destination nodes (the distribution centers and Brisbane seaport).

We assume a supply capacity of 50 and 55 heads at the production regions closest to Quilpie and Morven, respectively. We consider the average weight of the cattle to be 1000 kg. The average carcass weight depends on different factors such as fat tissues, muscle score and so on. However, we assume the average carcass weight to be 60 % of the cattle's weight. Service time is considered at each node which is defined transit time. We also assume a transit time of 30 min at each terminal for changing the transport mode, which includes loading, unloading and waiting times. In this research, we are focusing on the distribution of meat products, which have a limited shelf life, from the abattoir to the destination nodes. Thus, the travel time, which is dependent on road traffic condition, may impact on the quality of the meat products and, consequently, their final selling price. To avoid these issues and to keep the quality of the meat products at the required level, we assume the threshold T^s to be 3 1/2 h for the distribution of the meat products from the abattoir to the destination nodes. The penalty cost of $AUD0.005/s$ is applied for each kilogram of meat products distributed after T^s at each destination node. Table 4 summarises the cattle and meat products demand and the service times at the production regions, abattoir and destination nodes.

The distance between the nodes is calculated with Google Maps. We assume the 40-foot cattle trailer with a capacity of 30 heads for cattle distribution from the production regions to the abattoir and Brisbane seaport, and the 40-foot normal trailer with a capacity of 30 tons for transporting the meat products from the abattoir to the distribution centers and the Brisbane seaport. As we test the model for the small real-world example, we assume a train with a capacity of four trailers for cattle and meat products distribution. The fixed cost of using the cattle trailer and the normal trailer are assumed to be $AUD150$ and $AUD130$, respectively. We also assume a fixed cost of shipping each cattle or meat products trailer using a train to be $AUD300$. The parameters for calculating the fuel costs of the vehicles are extracted from previous literature, which are summarised in Table 5. We assume the speed level to be 80 km/h and 40 km/h for vehicles in the free flow interval ($m = 1$) and the traffic congestion interval ($m = 3$), respectively. A constant speed level of 80 km/h is considered for the train. We assume the fuel consumption rate for the train to be $0.00002/kg/km$.

Table 4
The cattle and meat products demand and service time at each node.

Parameters	P1	P2	A	DC1	DC2	Brisbane seaport
Cattle demand (heads)	–	–	–	–	–	30
Meat products (ton)	–	–	–	10	15	20
Service time (minutes)	30	40	40	15	15	30

Table 5
The description of vehicle parameters.

Notations	Description	Typical value
μ	Curb weight	6350
N^e	Engine speed (rev/s)	33
Φ	Engine friction factor (kJ/rev/L)	0.2
ι_k	Engine displacement (L)	5
τ	Fuel-to-air mass ratio	1
φ	Heating value of a typical diesel fuel (kJ/g)	44
ψ	Conversion factor (g/l)	737
ξ	Vehicle drive train efficiency	0.45
ω	Efficiency parameter for diesel engines	0.45
G	Gravitational constant (m/s^2)	9.81
C^e	Coefficient of rolling resistance	0.01
C^d	Coefficient of aerodynamic drag	0.7
ρ	Air density (kg/m^3)	1.2041
A_k	Frontal surface area (m^2)	9
θ	Road angle	0
P_f	Fuel price per liter (AUD)	1.6
δ	Unit CO_2 emissions price (AUD/kg)	0.44
σ	CO_2 emitted by unit fuel consumption (kg/L)	2.66

Source: Cachon (2014), Demir, 2012 and Babagolzadeh et al. (2020).

Computational experiments and analysis.

In this study, we preferred an exact method to analyse the effect of using multimodal transport. We intend to show how a multimodal transport network can improve efficiency, reliability and economic costs considering the traffic conditions, animal welfare issues and a carbon tax policy. To do so, the commercial optimisation solver, Cplex 12.3, which is the optimization solver based on branch-and-cut algorithm and an Intel i7 CPU (3.6 GHz processor and 16 GB RAM) are used to solve the proposed model for the case study. The running time was set to 7200 s and the model reached optimal solutions using the data obtained from the case study.

The following performance indicators are considered: (i) transport costs including fixed and fuel costs of a rail–road multimodal transport network; (ii) quality loss costs as a result of a meat threshold distribution violation; (iii) animal welfare reduction costs; and (iv) emission costs arising from fuel consumption of transport modes. The results are used to compare the unimodal and multimodal networks to identify the most effective network when considering animal welfare issues, traffic conditions and a carbon tax policy. Finally, sensitivity analyses are conducted on the animal welfare reduction costs and on the unit penalty costs to demonstrate the effect of their changes on the economic costs and the network configuration.

The optimal network configuration and the optimal values of the objective functions are presented in Table 6 and Fig. 2, respectively, when the rail–road multimodal network is considered. The optimal solution uses mostly vehicles for transporting cattle from the production regions to the abattoir because that occurs mostly in the regional area which does not have heavy traffic congestion. Consistent with Australia's transport access limitations, particularly in regional Australia, an earlier study by Wythes et al. (1980), found that in Australia, all livestock were transported by road within the country, except for some long-haul rail transport of cattle in Queensland, where cattle are trucked by

Table 6
The optimal value of the objective functions under a rail–road multimodal network (AUD).

Transport costs	Quality loss costs	Animal welfare reduction costs	emissions costs	Total cost
5336.9	6209.99	9379.5	5027.41	25953.8

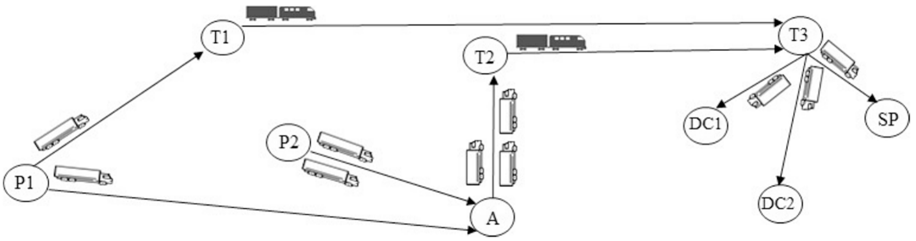

Fig. 2. The general view of the network configuration in the optimal solution of the multimodal network. (P: production region, T: terminal, A: abattoir, DC: distribution center and SP: Brisbane seaport).

road and then by rail over 1400 km to meat plants. The past three decades of research in this context has supported this finding, with strong and wide agreement on the importance of roads for rural Australia (Li and Hensher, 2009; Kneebone, 1997; Lignier, 2011), and freight transport is heavily emphasised (Nutley, 2003). McAuley (2010) highlighted that in regional Australia, while large numbers of train crossings across roads exist, low traffic volumes mean that delays are minimal. However, the model uses a train to distribute meat products from the abattoir to urban areas because of traffic congestion. Vehicles are used for meat distribution in inner city as vehicles provide a more flexible service in terms of destination and size of load. As can be seen from the results, shipment consolidation is not applied in the meat products' distribution due to the penalty imposed when vehicles arrive at the destination nodes after the threshold level for meat distribution is reached. A train is used for transporting cattle from a production region to the Brisbane seaport because it consumes less fuel and reduces animal welfare issues over the long distance. Regarding fuel consumption, one of the advantages of multimodal freight transport is the possibility of modal shift defined by partially or fully transferring from one mode (i.e., road) to the other (i.e., rail) in the network when freight is being shipped to its final destination. Bauer et al. (2010) highlight that this flexibility afforded by modal shift offers ways to reduce the environmental impacts of freight transport, by using more fuel efficient means of transport. As multimodal operations are increasingly studied and highlighted as a lower-emission and more energy- efficient alternative, its benefits have become increasingly apparent (Lammgård, 2012). The choice to shift from a road-only to a multimodal road-rail operation benefits from the trains' main attributes including: significantly larger load capacity than trucks (Janic, 2007) and a less carbon intensive form of transport (de Miranda Pinto et al., 2018). Regarding enhanced animal welfare in the use of rail transport, Miranda-De La Lama et al. (2014) concur that rail transport may have less of a negative impact on welfare compared with road transportation, as there is a handler to look after the animals and there are fewer changes of direction. Using a vehicle to transport cattle from a production region direct to the Brisbane seaport would increase the animal welfare reduction costs by 10.5 % while decreasing transport costs and emission costs by 9.18 % and 1.53 %, respectively, largely due to the drop in the fixed cost of vehicles and travel distance in our example.

To evaluate the performance of the rail–road multimodal model, we implement the proposed model with the real-world example, considering only the unimodal network and comparing the results with those obtained from the rail–road multimodal network. The optimal values of the objective functions obtained from the unimodal network are reported in Table 7.

As can be seen from the results, transport costs decrease by around 33 % which is driven exclusively by a reduction in the fixed cost of vehicles. Emission costs drop by only 1 % due to a reduction in the travel distance. However, using a unimodal network only can increase the costs associated with animal welfare reduction and quality loss by 10.5 % and 117.39 %, respectively, which would lead to an increase in the total cost by 24.87 %. The results suggest that the rail–road multimodal network is more desirable from the economic and animal welfare perspectives. However, the unimodal network is preferred for reducing fuel consumption and, consequently, emissions from the transport operations as the multimodal network makes the travel time much longer.

Table 7
The optimal value of the objective functions under the unimodal network (*AUD*).

Transport costs	Quality loss costs	Animal welfare reduction costs	emissions costs	Total cost
3570.52	13,500	10363.5	4976.54	32410.56

The question of whether a long journey can be managed better if the livestock are unloaded (with food and water) for resting places is not answered definitively in the literature, for all situations. A change in transport mode requires the unloading of cattle from one form of transport and re-loading to the new form of transport. Rail transport may be less common since animals have to be transported to a station and reloaded, thus increasing the adverse effects of loading, while possibly lengthening total journey time (Lambooij, 2007). This unloading and re-loading may be considered a break in the transport journey allowing cattle to use different muscles and shift into different spaces. Miranda-De La Lama et al. (2014) have suggested that rail transport has less of a negative impact on animal welfare compared with road transportation as there is a handler to look after animals and there are fewer changes of direction. Transported livestock often experience stress in the loading processes. However, during longer journeys cattle have time to recover from the stress of loading before they are unloaded (Fisher et al., 2009). Transport breaks or rest stops may benefit animal fatigue and hydration in the short term, but such stops may add extra loading and unloading events and prolong the overall duration of a journey (Fisher et al., 2009).

As the Australian government plans a new train line, the findings of this study show that it is possible for the government to reduce cattle and meat distribution costs by constructing the terminals closer to the main production regions and the abattoirs.

Sensitivity analysis.

We analyse the effects of parameter changes on the economic costs and the network configuration in the proposed meat supply chain. We also explore how changing the parameters may impact on transport mode selection decisions. Sensitivity analyses are conducted on the differences between the coefficients of animal welfare reduction costs and the unit penalty costs.

Impact of changes in the ratio of road animal welfare reduction rate to the rate for rail.

This section examines the impact of changing the ratio of the rate of animal welfare reduction costs for road transport to the rate for rail transport on various economic costs and CO_2 emissions.

As can be seen from Fig. 3, increasing the ratio of animal welfare reduction rate for road transport to the rate for rail transport from 0.6 to 1.5 does not lead to any significant changes in transport costs and emissions costs as the network configuration does not change and the model uses the unimodal network to transport cattle. However, it can result in the rise in animal welfare reduction costs and the total cost by about 126 % and 28.7 %, respectively.

A further increase in the ratio, say, from 1.5 to 1.8 can change the

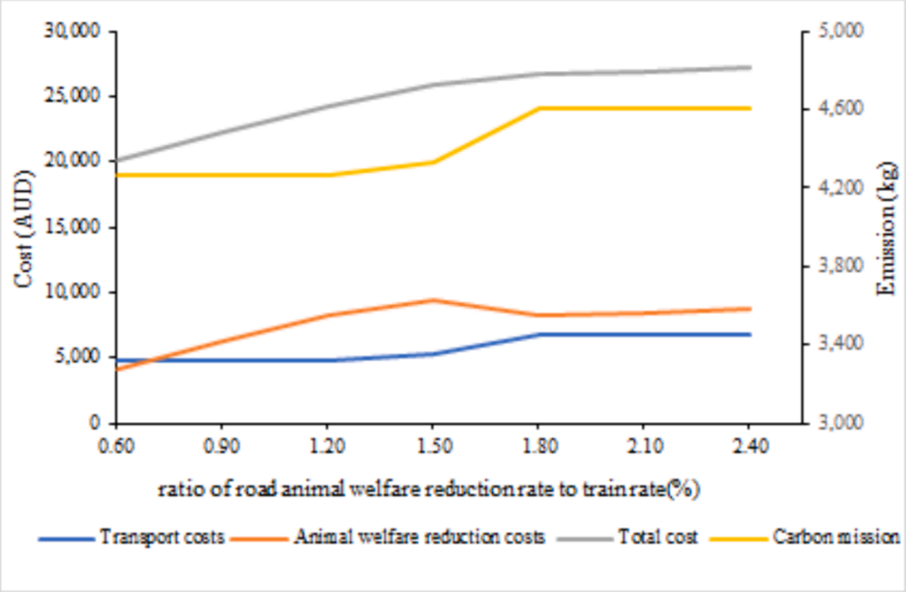

Fig. 3. The impact of changing the ratio of road animal welfare reduction rate to the rate for rail transport on different costs and CO2 emissions.

configuration of the model when using the multimodal network. It leads to a considerable growth in emissions costs and transport costs by about 6.2 % and 28.3 %, respectively, as a result of increases in the travel distance and the fixed cost of vehicles. It can also increase total cost by only a 2.7 %. However, it provides a reduction of about 11.8 % in animal welfare costs.

It can be observed that the continued increase of the ratio from 1.8 to 2.4 does not lead to any changes in the network configuration, transport costs and emissions costs. It would increase total costs by 5.7 % as a result of increasing animal welfare reduction costs in the multimodal network. Therefore, it is important to measure the animal welfare reduction coefficient and to consider it when selecting the most suitable transport mode and network configuration.

Impact of the change in unit penalty costs.

The sensitivity analysis is performed on the unit penalty costs to explore its impact on economic costs, the value which is used to calculate quality loss costs (delay multiplied by the load) and to determine the transport network configuration. Fig. 4 depicts the impact of changes in the unit penalty costs on the transport costs, total cost and quality loss costs. Fig. 4 indicate that if the penalty was not considered for meat product delivery later than the expected threshold, the unimodal transport network is preferred as it leads to lower economic costs due to the decrease in travel distance and the number of vehicles required, but it could lead to a higher value used to calculate the quality loss due to the traffic congestion. The model suggests that shipment consolidation is needed whenever possible.

In our case, it appears that an increase in unit penalty costs, say, from 0 to *AUD*0.002 can increase the total cost and transport costs by about 21 % and 25.9 %, respectively, by using the road–rail multimodal network for part of the meat products distribution. This results in longer travel distances and requires more vehicles. However, it has a higher effect on the value involved in calculating the quality loss costs. That is, the value involved in calculating the quality loss costs decreases by about 54.5 % as a result of avoiding traffic congestion in some legs of the journey.

The results show that the extended range of the unit penalty costs from *AUD*0.002 to *AUD*0.003 can lead to the use of the road–rail multimodal network only for meat product distribution to avoid a massive increase in quality loss costs. It means about a 11.3 % reduction in the value of the quality loss costs. However, the total cost and

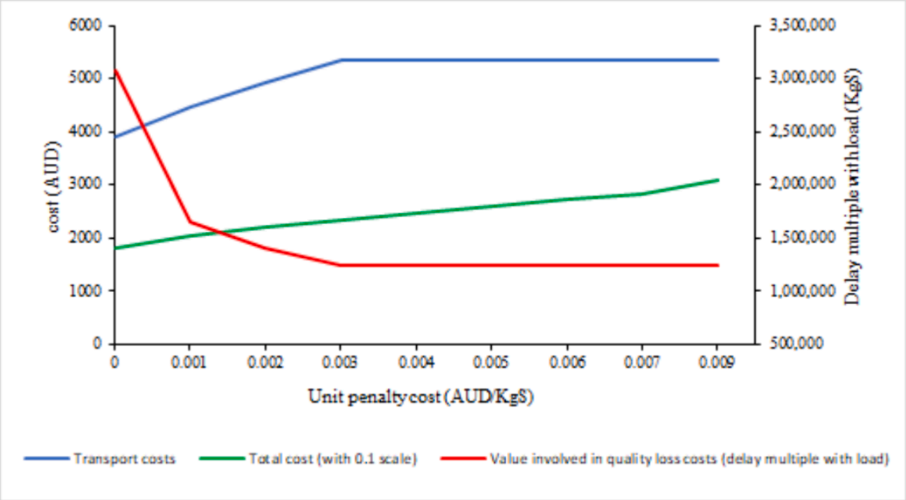

Fig. 4. The impact of changing the unit penalty costs on different costs and the value involved in the quality loss costs calculation.

transport costs increase by about 8.6 % and 6 %, respectively.

Fig. 4 illustrates that further increases in unit penalty costs cannot lead to any changes in transport costs and the value of quality loss costs. It only has a direct impact on the total cost. The findings of this research suggest that, in this case, a road–rail multimodal network is more beneficial in terms of reducing quality loss costs because heavy road traffic congestion in some legs of the journey may be avoided. However, it would not be a cost-efficient transport network in terms of transport costs and the emissions generated because of the significantly increased travel distance and the number of vehicles required.

6. Conclusion

The rise in road traffic congestion in Australia has increased delivery time significantly and has brought challenges to the transport and logistics sector in satisfying the growing demand for high quality products. Australia is the world's main meat producer. The quality of its meat products can be influenced by animal welfare issues during transportation. To respond to these challenges and to improve the reliability and efficiency of the transport network, it is important to integrate different transport modes when managing supply chains.

This paper proposes a decision support model to explore the impact of using a road–rail multimodal transport network on economic costs and animal welfare reduction costs in a meat supply chain. The proposed model simultaneously considers road traffic congestion, animal welfare, the quality of meat products and the environmental impact. The aim of the model is to minimise transport costs, animal welfare reduction costs, quality loss costs and emissions costs.

The model is evaluated using the meat supply chain case of Queensland, Australia. The results show that the proposed framework could help develop a reliable and cost-efficient multimodal transport network in the meat supply chain. It would be possible to decrease the total cost by about 24.87 % if a road–rail multimodal network is used along with a unimodal network in the meat supply chain in south-eastern Queensland. The results indicate that using a road–rail multimodal network for long distances can provide a better performance in terms of animal welfare issues and the quality of the products. It can lead to 10.5 % and 117.39 % reduction in animal welfare costs and quality loss costs, respectively, compared with using a unimodal transport network only. However, a unimodal network is recommended in our example in terms of transport costs and, consequently, emissions costs as using a multimodal network can lead to significant increases in travel distances and the number of vehicles required.

We conduct sensitivity analyses on the ratio of animal welfare reduction rate for road transport to the rate for rail transport and unit penalty costs, which can provide insights for decision makers to make the best decisions about transport mode selection in each part of the meat supply chain to improve the reliability and efficiency of the entire chain. Various factors influence public concerns about animal welfare. Animal stress, injury and mortality rates during transport are major concerns (Bozzo et al., 2021). In addition, long transport routes and inadequate rest, food and water supplies for livestock also concern consumers (Bozzo et al., 2021). We observe that the road–rail multimodal network would benefit more if animal welfare issues were prioritised. Therefore, it is important for decision makers to consider animal welfare, which influences the quality of the meat products, when making transport mode selection decisions. In addition, our experiments on unit penalty costs indicated that higher unit penalty costs can lead to the use of a multimodal network to avoid heavy road traffic congestion and the increases in quality loss costs. These findings can help the decision makers and meat supply chain participants to make more informed decisions in planning and developing transport networks and logistics facilities. For instance, in the case where there is heavy road traffic congestion, the road–rail multimodal network is more beneficial in terms of reducing quality loss costs. However, if the congestion problem is not serious, the road–rail multimodal network should not be preferred choice. Logistics companies should have the flexibility to adjust their transport modes and network as the road conditions change to achieve a balance between meat quality and transport costs. If needed, our model can be easily modified and extended for a wider application with other transport modes and objectives included.

CRediT authorship contribution statement

Mahla Babagolzadeh: Writing – original draft, Formal analysis, Conceptualization. **Yahua Zhang:** Writing – review & editing, Writing – original draft, Supervision. **Hang Yu:** Writing – review & editing, Methodology. **Jianming Yong:** Writing – review & editing, Supervision. **Tarryn Kille:** Writing – review & editing, Supervision. **Anup Shrestha:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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