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THE MODEL OF SELECTING MULTIMODAL TECHNOLOGIES FOR THE TRANSPORT OF PERISHABLE PRODUCTS

Paweł LELEŃ[1], Mariusz WASIAK[2]
[1, 2] Warsaw University of Technology, Faculty of Transport, Warsaw, Poland

Abstract:

The main goal of this paper is to provide an original model of selecting multimodal technologies for the transport of perishable goods. The model in particular refers to the transportability of cargoes. The features of cargoes that have the most impact on transportability were specified. Formal representations of the key elements of the model were presented and characterized, including: perishable cargoes, form of transported goods (solid, liquid, etc.), means of handling (including loading devices and transport means), transport routes, categories of human labor, multimodal technologies and transportation tasks. A formal representation of decision variables, as well as constrains and a criterion function were provided. The model bases on two main solution assessment criteria: cost criterion and cargo safety criterion. A cargo safety criterion in the model is composed of 18 partial criterion functions. Each of these functions directly affects one safety aspect of the transported cargo. The exemplary partial criteria of cargo safety included in the model are: acceptable transport time, minimum or maximum temperature in the cargo's direct surroundings, resistance to mechanical damage. In order to present a practical application of the presented mathematical model the paper shows also an example of selecting one of the multimodal technologies for the transport of perishable goods from the set of pre-defined types of multimodal transport technologies. The developed method uses different elements of the mathematical model provided in the paper, depending on the considered problem (including characteristics of cargo and their transport forms). For a significant group of perishable cargoes, it is not required to consider all defined criteria associated with cargo safety. The developed model allows for the accurate selection of transport technology for perishable cargoes for most transportation tasks. It should help to increase the efficiency of selection of multimodal transport technology for perishable products. The selected technology will then be characterized by the lowest transport cost and will ensure the safety of transported cargoes, as well as will meet other requirements determined by the transport task. As part of further work, it is possible to develop proposed method by considering additional characteristics of perishable cargoes.

Keywords: *transport technologies selection, mathematical model, cargo transportability, perishable cargo, multimodal transport*

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Contact:

1) plelen@wt.pw.edu.pl, 2) mwa@wt.pw.edu.pl [https://orcid.org/0000-0002-6173-7001]

1. Introduction

The characteristics and properties of perishable cargo may cause it to significantly deteriorate in quality due to conditions such as inappropriate temperature, humidity, lack of proper air flow, light exposure, exceedingly long transportation times, etc. (Madeyski and Lissowska, 1981). In the article below, perishable products are understood as products whose lifespan does not exceed 185 days.

Perishable products are primarily food products as well as other agricultural, horticultural and garden products; however, it should be kept in mind that other perishable products, which are neither food nor feed, exist. Some of these products include pharmaceuticals and medical products, as well as other chemical substances. It is estimated that nearly 50% of food products are perishable, requiring special conditions during warehousing and transport (Piekarska and Kondratowicz, 2011).

In the years 2012 to 2015, the number of perishable products transported increased significantly, but in 2016 it maintained a similar level as in the year 2015. In 2016, in Poland, 37,3% more food and drink products were transported than in the year 2011. The full details regarding the transport of perishable products in Poland for the years 2011-2016 is shown in Table 1.

Table 1. Transport of food and drink products for the years 2011-2016 in Poland (mln t)

Type of Transport	2011	2012	2013	2014	2015	2016
Road transport	102,2	102,1	128,9	120,7	140,2	140,4
Railway transport	1,2	1,5	1,7	2,2	1,9	2,1
Inland shipping	0,2	0,1	0,1	0,1	0,1	0,2
Total	103,6	103,8	130,7	123,0	142,2	142,7

Source: Own work based on (GUS, 2017; GUS, 2016; GUS, 2014; GUS, 2012)

The use of road transport in the transport of food and drink products in recent years was at 98,1 – 98,9%, however, in the year 2016, it decreased by 0,28 percentage points with respect to the year 2011. Railway transport, despite lower external costs, and in some cases, a preferential rate, is used for this type of transport to a small extent (Antonowicz, 2011).

The increase in production, and as a consequence, the transport of perishable products, determines the need to find new transport technologies and methods of improving the effectiveness of transport (Jacyna et al., 2015). The selection of transport technologies should take place in a manner which guarantees the safety of transported goods and, at the same time, ensure a high effectiveness of transport (Jacyna et al., 2018).

Some basic criteria considered for the selection of transport technologies for perishable products are: temperature, humidity, shocks and impacts, atmospheric composition, transport time and size and mass of loads (Leleń, Wasiak 2017).

Up until now, many studies have been developer and much research has been done on perishable products, with particular consideration of their characteristics, production technologies and storage. However, in terms of transport, this group of products has many issues which have only been described very generally (Horubała, 1975), (Leleń, 2015).

The issue which is described to a very small degree remains the selection of transport technologies for perishable products, especially in terms of multimodality. There is a lack of comprehensive method of selecting multimodal transport technologies for perishable cargo which takes into account the transportability analysis. In research thus far, the numerical expression of cargo transportability has only sporadically been presented (Bogdanowicz, 2008), (Bogdanowicz, 2012), (Madeyski and Lissowska, 1981), (Piekarska and Kondratowicz, 2011), (Tylutki, 1998).

In recent years, many complex studies on mathematical modeling in transport and logistics system design have been published (James et al., 2006), (Wasiak et al., 2017). Models dealing with the quantitative assessment of mechanical damage to fresh fruits and vegetables at each stage of the supply chain have also been developed (Colin and Zhiguo, 2014). The problem of excessive food waste has been emphasized in literature as a result of improperly selected transport technology as well as the erroneous flow of information at each stage of the transport-warehouse chain (Kaipia et al., 2013). Models pertaining to the optimization of energy usage during the distribution of refrigerated perishable products were also developed (Accorsi R. et al. 2017). In the remaining models, the flow of information in perishable product supply chains and the accompanying risk management using Petri nets, among others, is taken into account (Liu et al., 2018), (Bak 2018).

Economic models are also increasingly used, which allows the optimization of perishable product supply chains based on the net present value, *NPV*.
Select characteristics of loading space in terms of temperature, humidity and atmospheric composition of the load's direct environment, among others, are considered (Bogataj et al., 2017). It has been noted that, in the transport of perishable products, the highest profit is made at the cost of quality and freshness of products, therefore a compromise between the highest quality and lowest transport costs should be made (Grillo et al., 2017).
So far, the developed models dealing with designing perishable product supply chains to a greater or lesser degree, include a very detailed cost analysis, outlining vehicle routes and/or vehicle selection for given tasks (Nakandala et al., 2016), (Tijskens et al., 1996), (van der Vorst et al., 2009), (Wasiak 2016), as well as assessments of supply chain efficiency (Jacyna-Gołda, 2015), (Mańka and Mańka 2016), (Jacyna-Gołda et al., 2018) however an extensive analysis of characteristics and properties of loads, determining the load's transportability has not been considered. In the selection of the appropriate method of transport, it is also necessary to take into account the various features of the means of transport that affect the transport efficiency and ecology (Jankowski and Kowalski, 2018).
Given that a mathematical model of selecting multimodal technologies for the transport of perishable products containing a complex analysis of their transportability has not been developed to date, research has been undertaken to build such model.

2. Assumptions of the model

The model assumes the freedom to select a transport technology for certain transport tasks, including the possibility to select the labor resources and the engaged categories of human labor for each technology. It is given that transport technologies are defined by considering forms of transport, operations performed, travel routes as well as labor resources and categories of human labor.
However, the technological process in terms of technology is comprised of a series of organized operations. For each operations, the form of transported loads on which the operation is carried out, the transport path during this operation and the labor resources and categories of human labor which can be engaged to carry out the task.
The transportation tasks defined in the model deal with the movement of perishable products with the help of selected multimodal transport technologies. Moreover, perishable products have a series of characteristics which determine their transportability. Additionally, only the characteristics which most greatly impact a load's transportability are considered.
For every action listed in each technological process, it is possible to select various cargo packaging forms used in transport – in other words types of cargo. The impact of cargo type on transportability was taken into account. In the model, cargo, in terms of shape, is treated as cuboids in the smallest dimensions so it is possible to enter actual cargo dimensions.
It is assumed that the applied multimodal transport technologies must guarantee the safety of transported cargo, taking into account the conditions. Safety results from the type of transport technology and applied labor resources and cargo types. The assessment of multimodal technology selection in this model is carried out by taking into account two main types of criteria: cost minimization and cargo safety maximization.

3. General form and elements of the model

3.1. Elements of the model

The following elements were listed in the model:

- perishable cargo $\mathbf{BF}$,
- types of cargo $\mathbf{PF}$,
- labor resources $\mathbf{UF}$,
- categories of human labor $\mathbf{LF}$,
- transport routes $\mathbf{TF}$,
- multimodal transport technologies $\mathbf{TM}$,
- transportation tasks $\mathbf{ZM}$,
- organization $\mathbf{O}$, representing the way in which transportation tasks are completed, including decisions regarding transport technology selection as well as human and labor resources.

Having regard to the multimodal transport technology selection model for perishable products **MDT**, formally written as follows:

$$\mathbf{MDT} = \langle \mathbf{BF}, \mathbf{PF}, \mathbf{UF}, \mathbf{LF}, \mathbf{TF}, \mathbf{TM}, \mathbf{ZM}, \mathbf{O} \rangle \tag{1}$$

3.2. Perishable cargo

Perishable cargo $\mathbf{BF}$ was modeled taking into account the set of numbered load types

$\mathbf{B} = \{1, ..., b, ..., B\}$ and the set of their characteristics $\mathbf{F_B}$. In the model, the following characteristics of these loads were considered:

– dimensions of one item or packaging unit (length w_{bx}, width w_{by}, height w_{bz}) (m),
– mass and volume of one cargo unit or one packaging unit with load m_b (kg), V_b (m^3),
– cryoscopic temperature t_{kr} (K) as well as the lowest and highest allowable temperature during transport $t_{\min}$, $t_{\max}$ (K) and its permissible fluctuations Δt_{dop} (K),
– allowable storage and transport time in the appropriate conditions t_{pt} (h),
– lowest and highest allowable air humidity during transport $\phi_{\min}$, $\phi_{\max}$ (%) and its permissible fluctuations $\Delta\phi_{dop}$ (%),
– the amount of hourly ethylene production during transport ρ (μl/(kg·h)) and the sensitivity to the presence of ethylene in the atmosphere θ (–),
– the degree to which the application of a modified atmospheric composition is required ma (–),
– resistance to mechanical damage due to the dynamic impacts $f_{\max d}$ and static impacts $f_{\max}$ (N/m^2),
– sensitivity to the effects of UV radiation and light ws (–), susceptibility of leaks occurring from cargo wc (–) and water sensitivity ww (–),
– cargo unit price k_b (PLN/kg).
– Therefore the set of characteristics of perishable cargo types has the following form:

$$\mathbf{F_B} = \{(w_{bx}(b), w_{by}(b), w_{bz}(b), m_b(b), V_b(b), t_{kr}(b), t_{\min}(b), t_{\max}(b), \Delta t_{dop}(b), \phi_{\min}(b), \phi_{\max}(b), \Delta\phi_{dop}(b), \rho(b), \theta(b), t_{pt}(b), ma(b), f_{\max d}(d), f_{\max}(b), ws(b), wc(b), ww(b), k_b(b)) : b \in \mathbf{B}\}$$

3.3. Types of cargo in transport

Types of cargo significantly influences its transportability. Among the most common cargo packaging forms, the following are identified:

– loose cargo (unpacked),
– packaging units, multiple packages or transport packages,
– pallet units, most commonly formed using pallets of preferential size 800 x 1200 mm, including box pallets,
– packets, in which loads are formed with the help of additional binding products,
– small, medium and large containers, or other intermodal transport loading units (semi-trailers, roller containers, etc.)

In the model, transport forms $\mathbf{PF}$ were represented taking into account the set of numbers of transport forms $\mathbf{P} = \{1, ..., p, ..., P\}$ and the set of their characteristics $\mathbf{F_P}$. In terms of selecting multimodal transport technology, characteristics of forms of cargo transport include:

– maximum external dimensions (length w_{px}, width w_{py}, height w_{pz}) (m),
– resistance to mechanical damage due to static impacts $f_{p\max}$ and dynamic impacts $f_{p\max d}$ (N/m^2),
– ability to absorb ethylene φ_p (μl/h) and gas permeability pg (–),
– ability to protect cargo from the effects of water ow (–),
– minimum temperature of air $t_{\min p}$ (K), maximum temperature of air $t_{\max p}$ (K) and maximum fluctuation of air temperature in the direct environment of cargo Δt_{rzp} (K),
– possibility of atmospheric composition modification in the direct environment of cargo w_p (–), the possibility to change temperature in the direct environment of cargo w_t (–) and the ability to change humidity in the direct environment of cargo w_ϕ (–),
– minimum air humidity $\phi_{\min p}$ (%), maximum air humidity $\phi_{\max p}$ (%) and maximum fluctuations of air humidity in the direct environment of cargo $\Delta\phi_{rzp}$ (%),
– cargo leak integrity sz (–),
– tare mass m_p (kg),

– acceptable mass of the en tire unit load Q (kg) and its volume V (m^3),
– ability to protect cargo from UV radiation and light os_p (–),
– external dimensions (length w_{lx}, width w_{ly}, height w_{lz}) (m), preferential dimensions (length w_{lxp}, width w_{lyp}, height w_{lzp}) (m) and volume V_p (m^3).

Considering the set of transport form characteristics, they are formally defined as follows:

$$\mathbf{F_P} = \{(w_{px}(p), w_{py}(p), w_{pz}(p), f_{p\max}(p), f_{p\max d}(p), \varphi_p(p), pg(p), ow(p), w_p(p), w_t(p), w_\phi(p), t_{\min p}(p), t_{\max p}(p), \Delta t_{rzp}(p), \phi_{\min p}(b), \phi_{\max p}(b), \Delta\phi_{rzp}(b), sz(p), m_p(p), Q(p), V(p), os_p(p), w_{lx}(p), w_{ly}(p), w_{lz}(p), w_{lxp}(p), w_{lyp}(p), w_{lzp}(p), V_p(p)) : p \in \mathbf{P}\}$$

3.4. Labor resources

Labor resources $\mathbf{UF}$ were represented by accounting for the number of their types $\mathbf{U} = \{1,...,u,...,U\}$ and the set of their characteristics $\mathbf{F_U}$.

Transport resources and loading devices are characterized by separate meanings in the technological process. Keeping this fact in mind, the set of numbers of the types of labor resources $\mathbf{U}$ was decomposed into:
– the set of numbers of types of transport resources $\mathbf{U}1$,
– the set of numbers of types of loading devices $\mathbf{U}2$.

Consequently, the model considers two sets of labor resource characteristics, the set of transport resource characteristics $\mathbf{F_{U1}}$ and the set of loading device characteristics $\mathbf{F_{U2}}$.

Among the characteristics of transport resources, the following are listed:
– internal dimensions of loading space (length w_{ux}, width w_{uy}, height w_{uz}) (m) and volume V_{dop} (m^3) as well as allowable load capacity Q_{dop} (kg),
– preferential dimensions of a loading unit (length w_{uxp}, width w_{uyp}, height w_{uzp}) (m),
– minimum temperature $t_{\min r}$ (K), maximum temperature $t_{\max r}$ (K) and maximum temperature fluctuation in the loading space during transport Δt_{rz} (K),
– minimum humidity $\phi_{\min p}$ (%), maximum humidity $\phi_{\max p}$ (%) and maximum humidity fluctuation in the loading space during transport $\Delta\phi_{rzp}$ (%),
– volume of ethylene which may be removed from the loading space in the unit during transport φ (μl/h),
– average transport speed v_{sr} (km/h),
– ability to modify the atmospheric composition in the loading space w (–), ability to ensure protection against the direct effect of water on the cargo ow_u (–) and the ability to protect the cargo against UV radiation and light os_u (–),
– unit transport cost depending on mileage k_{ts} (PLN/(km) and unit transport cost depending on transport time k_{tt} (PLN/h),
– the highest value of static impacts $f_{u1\max}$ and dynamic impacts $f_{u1\max d}$, to which the cargo is subjected to (N/m^2),
– ability to work with specified loading devices $\mathbf{UU}$ (–), servicing cargo transport forms $\mathbf{P_{U1}}$ (–) and labor positions $\mathbf{LSP}$ (–).

Considering the above, the set of types of transport resource characteristics has the form below:

$$\mathbf{F_{U1}} = \{(w_{ux}(u), w_{uy}(u), w_{uz}(u), V_{dop}(u), Q_{dop}(u), w_{uxp}(u), w_{uyp}(u), w_{uzp}(u), t_{\min r}(u), t_{\max r}(u), \Delta t_{rz}(u), \phi_{\min p}(u), \phi_{\max p}(u), \Delta\phi_{rzp}(u), \varphi(u), v_{sr}(u), w(u), ow_u(u), os_u(u), k_{ts}(u), k_{tt}(u), f_{u1\max}(u), f_{u1\max d}(u), \mathbf{UU}(u), \mathbf{P_{U1}}(u), \mathbf{LSP}(u)) : u \in \mathbf{U}1\}$$

Loading devices are characterized considering their:
– lifting/carrying capacity F_Q (N) and theoretical efficiency W (t/h) and the theoretical efficiency correction factor g_t (–),
– unit (hourly) labor cost k_{j2} (PLN/h),
– serviced cargo transport forms $\mathbf{P_{U2}}$ (–),

– the highest value of static impacts $f_{u2\max}$ and dynamic impacts $f_{u2\max d}$, to which the cargo is subjected to (N/m^2),
– labor positions $\mathbf{LSP}$,
– the maximum dimensions of serviced cargo load (length w_{u2x}, width w_{u2y}, height w_{u2z}) (m) and preferential cargo dimensions (length w_{u2xp}, width w_{u2yp}, height w_{u2zp}) (m).

Keeping in mind the listed characteristics, the set of characteristics of the loading device types is noted as follows:

$$\mathbf{F}_{\mathrm{U2}} = \{(F_Q(u), W(u), g_t(u), k_{j2}(u), \mathbf{P}_{\mathbf{U2}}(u), f_{u2\max}(u), f_{u2\max d}(d), f_{u2\max d}(d), \mathbf{LSP}(u), w_{u2x}(u), w_{u2y}(u), w_{u2z}(u), w_{u2xp}(u), w_{u2yp}(u), w_{u2zp}(u)) : u \in \mathbf{U}2\}$$

3.5. Categories of human labor

Each action completed in the technological process requires labor resources and/or workers. At the same time, most labor resources require hiring workers of given human labor categories.

Categories of human labor $\mathbf{LF}$ were modeled considering the set of their numbers $\mathbf{L} = \{1,\ ...,\ l,\ ...,\ L\}$ and the set of their characteristics $\mathbf{F_L}$. Among the characteristics of human labor categories, the model includes the unit labor cost k_l (PLN/h) and the possibility to hire for each labor position $\mathbf{SLU}$ (–). Therefore, the set of characteristics of categories of human labor has the form:

$$\mathbf{F_L} = \{k_l(l), \mathbf{SLU}(l)) : l \in \mathbf{L}\}$$

3.6. Shipment route

Shipment routes $\mathbf{TF}$ in the developer model were designed taking into account the set of their numbers $\mathbf{T} = \{1,\ ...,\ t,\ ...,\ T\}$ and the set of their characteristics $\boldsymbol{F_T}$. At the same time, the characteristics of shipment routes were identified as length s (km), types of allowable labor resources $\mathbf{TU}$ (–), costs of infrastructure usage k_{dod} (PLN) and additional labor costs k_{dod2} (PLN). Thus, the set of shipment route characteristics is defined as:

$$\mathbf{F_T} = \{(s(t), \mathbf{TU}(t), k_{dod}(t,u), k_{dod2}(t,u,lsp(u),l)) : t \in \mathbf{T}, u \in \mathbf{U}, lsp(u) \in \mathbf{LSP}(u), l \in \mathbf{L}\}$$

3.6. Multimodal transport technologies

Various types of multimodal technologies are determined by:
– types of actions completed in a given sequence,
– characteristics of types of cargo used in subsequent stages of transport,
– characteristics of selected labor resources,
– characteristics of selected categories of human labor,
– characteristics of selected transport routes.

Each multimodal transport technology requires the engagement of the appropriate human labor and labor resources (transport means, loading devices, devices necessary for forming loading units, etc.).

In the model, multimodal transport technologies $\mathbf{TM}$ are reflected by accounting for the set of numbers of technology types $\mathbf{D} = \{1,...,d,...,D\}$ and the set of technological processes in each technology $\mathbf{PT}$. It is also assumed that in each transport technology process identified in terms of technology d-th type, a certain number of actions can be listed and treated as elements of this process $E(d)$. Keeping this in mind, for a set transport technology process, an ordered set of action is defined as $\mathbf{I}(d) = \{1,...,e,...,E(d)\}$.

Technological process $PT(d)$ for a given (d-th) multimodal transport technology is written as a series of ordered fives, whose elements for the e-th action define the following:
type of cargo $pt_e(d)$, type of completed actions on it $nt_e(d)$, transport route $tt_e(d)$, potential labor resource applications $\mathbf{UT_e}(d)$ and categories of human labor $\mathbf{LT_e}(d)$. It is formally written as follows:

$$PT(d) = \langle (pt_e(d), nt_e(d), tt_e(d), \mathbf{UT_e}(d), \mathbf{LT_e}(d)) : e \in \mathbf{I}(d), pt_e(d) \in \mathbf{P}, nt_e(d) \in \mathbf{N}, tt_e(d) \in \mathbf{T}, \mathbf{UT_e}(d) \subseteq \mathbf{U}, \mathbf{LT_e}(d) \subseteq \mathbf{L} \rangle, d \in \mathbf{D}$$

3.7. Transportation tasks

In the developed model, each transportation task is represented accounting for the information regarding the types and amounts of products to be transported, dispatch and delivery location, pickup and delivery date[1], as well as the potential types of cargo and types of labor resources. Location acts as a sufficient characteristic of dispatch and delivery locations in the model.

The set of numbers of transportation tasks, for which multimodal transport Technologies are selected, is defined as $\mathbf{Z} = \{1,\ ...,\ z,\ ...,\ Z\}$, where the transportation task number z is denoted as $ZT(z)$ and defined as follows:

$$ZT(z) =< \mathbf{B}(z), \mathbf{M}(z), m_p(z), m_d(z), t_p(z), t_d(z), \mathbf{P}(z), \mathbf{U}(z) >, z \in \mathbf{Z}$$

where:

- $\mathbf{B}(z)$ – set of numbers of types of cargo for the *z*-th transportation task,
- $\mathbf{M}(z)$ – set of individual types of cargo masses for the *z*-th transport task,
- $m_p(z)$ – pickup location of cargo for the *z*-th transport task,
- $m_d(z)$ – delivery location of cargo for the *z*-th transport task,
- $t_p(z)$ – required cargo pickup date for the *z*-th transport task,
- $t_d(z)$ – required cargo delivery date for the *z*-th transport task,
- $\mathbf{P}(z)$ – set of numbers of potentially applicable types of cargo for the *z*-th transport task,
- $\mathbf{U}(z)$ – set of numbers of types of labor resources which may be used to complete the z-th transport task.

3.8. Decision variables

Considering the assumptions of the model and research goals, it has been established that decision variables should primarily describe:

– transport technologies which should be applied in order to complete the given transportation tasks,
– types of labor resources necessary to complete individual actions in the given transport technologies,
– categories of human labor necessary to operate individual labor resources applied to complete individual actions for the given transport technology.

In order to meet the needs of the designed model, three binary decision variables regarding: selection of a transport technology for tasks, selection of labor resources for completion of individual actions for a given technology and selection of human labor category to operate devices used to complete subsequent actions for transport technologies were defined:

$$x(z,d) \in \{0,1\}$$

when $x(z,d) = 1$, the *z*-th transportation task should be completed according to the *d*-th type of transport technology. In the opposite case, $x(z,d) = 0$

$$y(z,d,e,u) \in \{0,1\}$$

when $y(z,d,e,u) = 1$, then in order to complete the *z*-th transport task using the *d*-th type of transport technology to complete the *e*-th action, the *u*-th type of labor resource should be used. Otherwise, $y(z,d,e,u) = 0$

$$z(z,d,e,u,lsp(u),l) \in \{0,1\}$$

when $z(z,d,e,u,lsp(u),l) = 1$, then in order to complete the *z*-th transport task using the *d*-th type of transport technology to complete the *e*-th action using the *u*-th type of labor resource by hiring a worker of the *l*-th human labor category for the *lsp*(*u*)-th labor position. Otherwise, $z(z,d,e,u,lsp(u),l) = 1$.

3.9. Constraints

The constraints in this model result from the established assumptions, including the considered perishable cargo characteristics, loading form and transport means characteristics and multimodal transport technology characteristics.

The first constraint considered regards task completion:

$$\forall z \in \mathbf{Z} \quad \sum_{d \in \mathbf{D}(z)} x(x,d) = 1 \qquad (2)$$

[1] The required cargo pickup date is understood as the earliest possibile moment of pickup and the required cargo delivery date is the latest possibile moment of their delivery.

The following constraints deal with device (3) and worker (4) selection to complete the given actions:

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{I}(d) : \mathbf{UT_e}(d) \neq \varnothing \quad \sum_{u \in \mathbf{UT_e}(d)} y(z,d,e,u) = x(z,d) \tag{3}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{I}(d) : \mathbf{UT_e}(d) \neq \varnothing \quad \forall u \in \mathbf{UT_e}(d) \;\; \forall lsp(u) \in \mathbf{LSP}(u) \quad \sum_{l \in \mathbf{SUL}(u,lsp(u))} z(z,d,e,u,lsp(u),l) = x(z,d) \tag{4}$$

Constraints connected with transport temperature (5-7), air humidity during transport (8-10), atmospheric composition in the direct environment of the cargo (11-12), protection against detrimental effects of water (13), UV radiation and sunlight (14) and cargo leaks (15) were also considered. The next constraints result from physical properties of cargo, such as: mass (16), volume (17), external package dimensions and cargo units (18-23) and the external measurements of type of cargo (24-29).
The acceptable transport time is written as constraint (30). Cargo safety in terms of mechanical impacts is ensured in constraints (31)–(34). Constraint (32) and (34) ensures that the acceptable mechanical impact is not exceeded during transport and constraints (31) and (33) ensure that the acceptable mechanical impact is not exceeded during handling.
In the following constraints, the following are considered: compatibility of transport means and loading devices (35), transport means serviced by labor sources (36, 37) permitting labor means to travel along travel routes (38), and the allowable lifting capacity of loading devices (39).

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad t_{\min r}(u) \cdot [1 - w_t(pt_e(d))] + t_{\min p}(pt_e(d)) \cdot w_t(pt_e(d)) > y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)} \{t_{\min}(b)\} \tag{5}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad y(z,d,e,u) \cdot [t_{\max r}(u) \cdot [1 - w_t(pt_e(d))] + t_{\max p}(pt_e(d)) \cdot w_t(pt_e(d)] \leq \min_{b \in \mathbf{B}(z)} \{t_{\max}(b)\} \tag{6}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad y(z,d,e,u) \cdot [\Delta t_{rz}(u) \cdot [1 - w_t(pt_e(d))] + \Delta t_{rzp}(pt_e(d)) \cdot w_t(pt_e(d)] \leq \min_{b \in \mathbf{B}(z)} \{\Delta t_{dop}(b)\} \tag{7}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad \phi_{\min r}(u) \cdot [1 - w_\phi(pt_e(d))] + \phi_{\min p}(pt_e(d)) \cdot w_\phi(pt_e(d)) > y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)} \{\phi_{\min}(b)\} \tag{8}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad y(z,d,e,u) \cdot [\phi_{\max r}(u) \cdot [1 - w_\phi(pt_e(d))] + \phi_{\max p}(pt_e(d)) \cdot w_\phi(pt_e(d)] \leq \min_{b \in \mathbf{B}(z)} \{\phi_{\max}(b)\} \tag{9}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad y(z,d,e,u) \cdot [\Delta\phi_{rz}(u) \cdot [1 - w_\phi(pt_e(d))] + \Delta\phi_{rzp}(pt_e(d)) \cdot w_\phi(pt_e(d)] \leq \min_{b \in \mathbf{B}(z)} \{\Delta\phi_{dop}(b)\} \tag{10}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad pg(pt_e(d)) \cdot \varphi(u) + w_p(pt_e(d)) \cdot \varphi_p(pt_e(d)) \geq y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)} \{\theta(b)\} \cdot \sum_{b \in \mathbf{B}(z)} \rho(b) \cdot m(b,z) \tag{11}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad y(z,d,e,u) \cdot 0{,}5 \cdot w(u) \cdot w_p(pt_e(d)) \leq \min_{b \in \mathbf{B}(z)} \{ma(b)\} \tag{12}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d) \quad \max_{b \in \mathbf{B}(z)} \{ww(b)\} \cdot y(z,d,e,u) = \max\left\{ow(pt_e(d)); ow_u(u)\right\} \tag{13}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\max_{b \in \mathbf{B}(z)}\{ws(b)\} \cdot y(z,d,e,u) \le \max\left\{os_p(pt_e(d)); os_u(u)\right\} \quad (14)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \quad sz(pt_e(d)) \ge \max_{b \in \mathbf{B}(z)}\{wc(b)\} \cdot x(z,d) \quad (15)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{Q(pt_e(d)) - m_p(pt_e(d)); Q_{dop}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{m_b(b)\} \quad (16)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{V_p(pt_e(d)); V_{dop}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{V_b(b)\} \quad (17)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{w_{lx}(pt_e(d)); w_{ux}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{w_{bx}(b)\} \quad (18)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{w_{ly}(pt_e(d)); w_{uy}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{w_{by}(b)\} \quad (19)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{w_{lz}(pt_e(d)); w_{uz}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{w_{bz}(b)\} \quad (20)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{w_{lx}(pt_e(d)); w_{u2x}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{w_{bx}(b)\} \quad (21)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{w_{ly}(pt_e(d)); w_{u2y}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{w_{by}(b)\} \quad (22)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{w_{lz}(pt_e(d)); w_{u2z}(u)\right\} \ge y(z,d,e,u) \cdot \max_{b \in \mathbf{B}(z)}\{w_{bz}(b)\} \quad (23)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$w_{ux}(u) \ge y(z,d,e,u) \cdot \max\left\{w_{px}(pt_e(d)); \max_{b \in \mathbf{B}(z)}\{w_{bx}(b)\}\right\} \quad (24)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$w_{uy}(u) \ge y(z,d,e,u) \cdot \max\left\{w_{py}(pt_e(d)); \max_{b \in \mathbf{B}(z)}\{w_{by}(b)\}\right\} \quad (25)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$w_{uz}(u) \ge y(z,d,e,u) \cdot \max\left\{w_{pz}(pt_e(d)); \max_{b \in \mathbf{B}(z)}\{w_{bz}(b)\}\right\} \quad (26)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$w_{u2x}(u) \ge y(z,d,e,u) \cdot \max\left\{w_{px}(pt_e(d)); \max_{b \in \mathbf{B}(z)}\{w_{bx}(b)\}\right\} \quad (27)$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$w_{u2y}(u) \geq y(z,d,e,u) \cdot \max\left\{ w_{py}(pt_e(d)); \max_{b \in \mathbf{B}(z)}\{w_{by}(b)\}\right\} \tag{28}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$w_{u2z}(u) \geq y(z,d,e,u) \cdot \max\left\{ w_{pz}(pt_e(d)); \max_{b \in \mathbf{B}(z)}\{w_{bz}(b)\}\right\} \tag{29}$$

$$\forall z \in \mathbf{Z} \; \forall d \in \mathbf{D}(z) \;\; x(z,d) \cdot t_c(z,d) \leq \varepsilon \cdot \min_{b \in \mathbf{B}(z)}\{t_{pt}(b)\} \tag{30}$$

$$\forall z \in \mathbf{Z} \; \forall d \in \mathbf{D}(z) \; \forall e \in \mathbf{IL}(d) \; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\max\left\{ f_{p\max d}(pt_e(d)); \min_{b \in \mathbf{B}(z)}\{f_{\max d}(b)\}\right\} \geq y(z,d,e,u) \cdot f_{u2\max d}(u) \tag{31}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\max\left\{ f_{p\max d}(pt_e(d)); \min_{b \in \mathbf{B}(z)}\{f_{\max d}(b)\}\right\} \geq y(z,d,e,u) \cdot f_{u1\max d}(u) \tag{32}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\max\left\{ f_{p\max}(pt_e(d)); \min_{b \in \mathbf{B}(z)}\{f_{\max}(b)\}\right\} \geq y(z,d,e,u) \cdot f_{u2\max}(u) \tag{33}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\max\left\{ f_{p\max}(pt_e(d)); \min_{b \in \mathbf{B}(z)}\{f_{\max}(b)\}\right\} \geq y(z,d,e,u) \cdot f_{u1\max}(u) \tag{34}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$\min\left\{uu(u,ut_{e-1}(d)); uu(u,ut_{e+1}(d))\right\} \geq y(z,d,e,u) \tag{35}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IP}(d) \;\; \forall u \in \mathbf{U1} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$y(z,d,e,u) \leq \kappa(u, pt_e(d)) \tag{36}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$y(z,d,e,u) \leq \kappa 2(u, pt_e(d)) \tag{37}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{I}(d) \;\; \forall u \in \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$y(z,d,e,u) \leq \tau(tt_e(d),u) \tag{38}$$

$$\forall z \in \mathbf{Z} \;\; \forall d \in \mathbf{D}(z) \;\; \forall e \in \mathbf{IL}(d) \;\; \forall u \in \mathbf{U2} \cap \mathbf{U}(z) \cap \mathbf{UT_e}(d)$$
$$y(z,d,e,u) \cdot Q(pt_e(d)) \cdot g \leq F_Q(u) \tag{39}$$

3.10. Criterion function

There are two main solution assessment criteria in the model: cost criterion and cargo safety criterion. In the criterion function which guarantees the minimization of costs, the following elements are included:

– labor cost of transport means – $KU1(z,d,e,u)$,

– labor cost of loading devices – $KU2(z,d,e,u)$,

– labor cost of workers operating transport means – $KL1(z,d,e,u,lsp(u),l)$,

– labor cost of loading device operators – $KL2(z,d,e,u,lsp(u),l)$.

Considering the above and aforementioned decision variables of the cost minimization criterion was formally defined as follows:

$$\mathrm{F1}(\mathbf{Y},\mathbf{Z}) = \sum_{z\in\mathbf{Z}}\sum_{d\in\mathbf{D}(z)}\sum_{e\in\mathbf{I}(d)}\left[\sum_{u\in\mathbf{UT_e}(d)\cap\mathbf{U1}} y(z,d,e,u)\cdot KU1(z,d,e,u) + \sum_{u\in\mathbf{UT_e}(d)\cap\mathbf{U2}} y(z,d,e,u)\cdot KU2(z,d,e,u)\right] +$$
$$\sum_{z\in\mathbf{Z}}\sum_{d\in\mathbf{D}(z)}\sum_{e\in\mathbf{I}(d)}\sum_{u\in\mathbf{UT_e}(d)\cap\mathbf{U1}}\sum_{lsp(u)\in\mathbf{LSP}(u):u\in\mathbf{UT_e}(d)}\sum_{l\in\mathbf{SUL}(u,lsp(u))} \begin{matrix} z(z,d,e,u,lsp(u),l)\cdot \\ KL1(z,d,e,u,lsp(u),l)\end{matrix} + \qquad (40)$$
$$\sum_{z\in\mathbf{Z}}\sum_{d\in\mathbf{D}(z)}\sum_{e\in\mathbf{I}(d)}\sum_{u\in\mathbf{UT_e}(d)\cap\mathbf{U2}}\sum_{lsp(u)\in\mathbf{LSP}(u):u\in\mathbf{UT_e}(d)}\sum_{l\in\mathbf{SUL}(u,lsp(u))} \begin{matrix} z(z,d,e,u,lsp(u),l)\cdot \\ KL2(z,d,e,u,lsp(u),l)\end{matrix} \longrightarrow \min$$

The partial cost values in Equation 40 are determined according to the following dependencies:

$$KU1(z,d,e,u) = s(tt_e(d))\cdot k_{ts}(u) + \left[\frac{s(tt_e(d))}{v_{sr}(u)} + t_{dod}(e)\right]\cdot k_{tt}(u) + k_{dod}(tt_e(d),u) \qquad (41)$$

$$KU2(z,d,e,u) = \frac{k_{tt}(u)}{w(u)\cdot g_t(u)}\cdot\sum_{b\in\mathbf{B}(z)} m(b,z) + k_{dod}(tt_e(d),u) \qquad (42)$$

$$KL1(z,d,e,u,lsp(u),l) = \left[\frac{s(tt_e(d))}{v_{sr}(u)} + t_{dod2}(e,u,lsp(u),l)\right]\cdot k_l(l) + k_{dod2}(tt_e(d),u,lsp(u),l) \qquad (43)$$

$$KL2(z,d,e,u,lsp(u),l) = \left[\frac{1}{w(u)\cdot g_t(u)}\cdot\sum_{b\in\mathbf{B}(z)} m(b,z) + t_{dod2}(e,u,lsp(u),l)\right]\cdot k_l(l) + k_{dod2}(tt_e(d),u,lsp(u),l) \qquad (44)$$

As a cargo safety criterion in the model, 18 partial criterion functions were considered. Each of these functions directly affects one safety aspect of the transported cargo. Some examples of partial criteria of cargo safety included in the model are: acceptable transport time, minimum or maximum temperature in the cargo's direct surroundings, resistance to mechanical damage.

The general form of a partial cargo safety criterion is noted as:

$$\mathrm{F2}_k(\mathbf{X}) = \sum_{z\in\mathbf{Z}}\sum_{d\in\mathbf{D}(z)} x(z,d)\cdot w(k,z,d) \longrightarrow \max \qquad (57)$$

where:

$w(k,z,d)$ – partial transportability coefficient based on the *k*-th criterion for the *z*-th transport task completed using the *d*-th type of transport technology,

$x(z,d)$ – binary decision variable assuming the value of 1, when the *z*-th transport task should be completed using the *d*-th type of transport technology or 0 otherwise.

Considering the described elements of the developed mathematical model, it is possible to formulate and solve optimization tasks for many types of perishable products[2], where it is possible to find optimal solutions only in terms of costs or cargo safety, as well as in the sense of Pareto[3].

In an effort to present a practical application of the presented mathematical model, the next chapter describes a sample calculation regarding the selection of transport technology for a given transport task.

4. Case study

4.1. Multimodal transport technology selection algorithm

For the purposes of practical applications of the developed model, a multimodal transport technology selection algorithm was built (Fig. 1).

In the first stage of this algorithm, a systemization and input data entry is conducted, after which the identification of transport tasks and generation of transport technology variants is completed. For each

[2] Sample application of the developed model for transport technology selection optimization for perishable nonclimacteric cargo was described in (Leleń, Wasiak, 2018).

[3] Methods of multicriteria solution assessment were described, among others, Trzaskalik, 2014, Barford et al., 2011, Jacyna and Wasiak, 2015.

technological variant, values of transportability partial coefficients are determined, and variants for which at least one partial coefficient of transportability is equal to 0 are eliminated.
In the next stage, the type of optimization task is chosen based on the type of problem and data for this task is prepared. The optimization task is solved next considering the safety criterions and transport cost. Values of the following partial coefficients of transportability are determined and a multicriteria assessment of transport technology variants takes place.

4.2. Formulation of the problem

The problem of multimodal transport technology selection for a transport task is examined in this article, including the transport of two types of cargo: apples $b=1$ and pears $b=2$, in the amounts $\mathbf{M}(1)=\{3200;\ 4000\}$ kg. The cargo is to be transported from Tarczyn (mazovian voivodeship) $m_p(1)=1$ to Rotterdam (Holland) $m_d(1)=2$. The cargo can be undertaken at the earliest time $t_p(1)=0$ h, and the latest delivery time is set at $t_d(1)=148$ h. It is established that two types of cargo (packaging forms) are accepted – crates $p=1$ and pallet-crates $p=2$. In order to complete the task, 8 types of labor sources are accepted, $\mathbf{U}(1)=\{1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7,\ 8\}$ Five types of transport means $\mathbf{U}1(1)=\{1,\ 2,\ 3,\ 4,\ 8\}$ as well as four types of loading devices $\mathbf{U}2(1)=\{3,\ 5,\ 6,\ 7\}$ can be used to carry out separate actions as part of the technological process. Four possibly applicable transport technologies $\mathbf{D}(1)=\{1,\ 2,\ 3,\ 4\}$ have been defined. Technological processes for each technology have been graphically presented in Fig. 2.

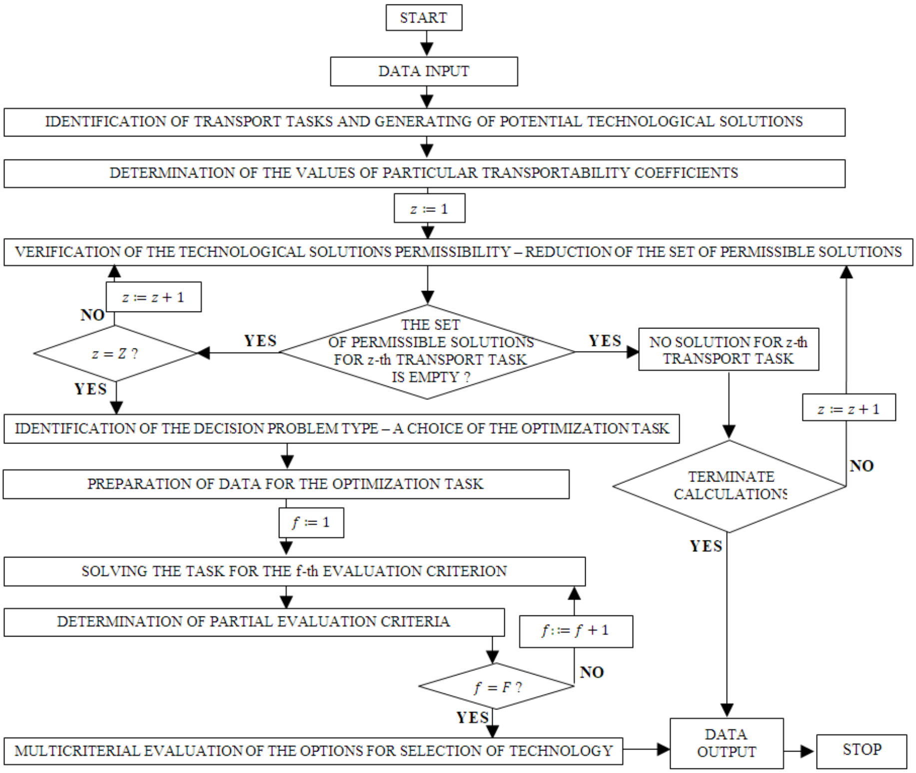
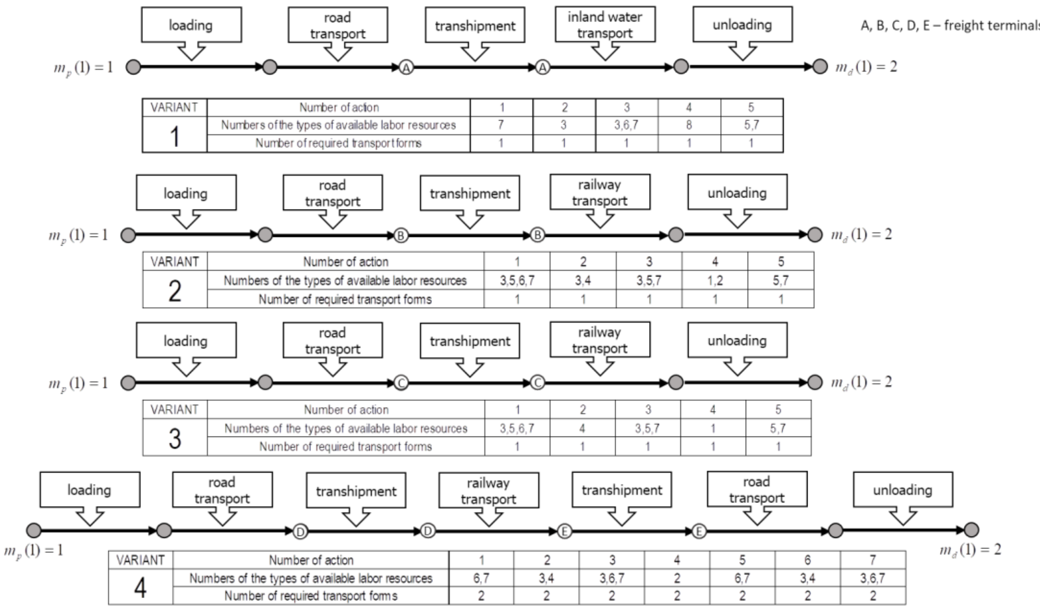


Fig. 1. Multimodal transport technology selection algorithm



VARIANT 1	1	2	3	4	5
Number of action	1	2	3	4	5
Numbers of the types of available labor resources	7	3	3,6,7	8	5,7
Number of required transport forms	1	1	1	1	1

VARIANT 2					
Number of action	1	2	3	4	5
Numbers of the types of available labor resources	3,5,6,7	3,4	3,5,7	1,2	5,7
Number of required transport forms	1	1	1	1	1

VARIANT 3					
Number of action	1	2	3	4	5
Numbers of the types of available labor resources	3,5,6,7	4	3,5,7	1	5,7
Number of required transport forms	1	1	1	1	1

VARIANT 4							
Number of action	1	2	3	4	5	6	7
Numbers of the types of available labor resources	6,7	3,4	3,6,7	2	6,7	3,4	3,6,7
Number of required transport forms	2	2	2	2	2	2	2

Fig. 2. Technological processes for different types of technologies

Two types of categories of hirable human labor $\mathbf{L}(1)=\{1,\ 2\}$ are foreseen to carry out actions in accordance with the technological process. The set of movement route numbers have also been defined $\mathbf{T}(1)=\{1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 7,\ 8,\ 9,\ 10,\ 11,\ 12\}$.

Known characteristics of various types of human labor categories, for example, hourly cost of work, 18 and 22 PLN respectively, and possibility to hire for various positions $\mathbf{SLU}(1)=\{1,\ 2\}$, $\mathbf{SLU}(2)=\{1,\ 2,\ 3\}$, as well as characteristics of cargo of various types are presented in Table 2.

Characteristics of movement routes include their length, additional movement cost as well as sets of numbers of device types which can move along them. Characteristics of various movement routes are shown in Table 3.

Characteristics of transport means are presented in Table 4 and characteristics of loading devices are found in Table 5.

Table 2. Cargo characteristics

Parameter	Unit	$b=1$	$b=2$
$w_{bx}(b)$	m	0,6	0,6
$w_{by}(b)$	m	0,4	0,4
$w_{bz}(b)$	m	0,3	0,3
$m_b(b)$	kg	20	18
$V_b(b)$	m^3	0,072	0,072
$tk_r(b)$	K	271,15	270
$\Delta t_{dop}(b)$	K	1	0,7
$t_{max}(b)$	K	278,15	277
$t_{min}(b)$	K	276,15	272,15
$\varphi_{min}(b)$	%	90	90
$\varphi_{max}(b)$	%	95	95
$\Delta\varphi_{dop}(b)$	%	3	3
$\rho(b)$	µl/(kg*h)	10	2
$t_{pt}(b)$	h	2400	1000
$ma(b)$	-	0,5	0
$\theta(b)$	-	1	1
$f_{max}(b)$	N/m^2	100	55
$f_{maxd}(b)$	N/m^2	55	34
$ws(b)$	-	1	1
$wc(b)$	-	1	1
$ww(b)$	-	1	1
$k_b(b)$	PLN/kg	0,4	1

Table 3. Characteristics of movement routes

Route number t	Length of route (km) $s(t)$	Numbers of types of labor sources allowed to move along the route $\boldsymbol{TU}(t)$	Additional costs associated with moving along route (PLN/km) $k_{dod}(t)$
1	1320	1, 2	0
2	95	3, 4	0
3	1240	1, 2	0
4	108	3, 4	0
5	1100	3, 4	0
6	245	1, 2, 3, 4	0
7	0,15	3, 5, 6, 7	0
8	0,02	3, 5, 6, 7	0
9	0,25	3, 5, 6, 7	0
10	0,2	3, 5, 6, 7	0
11	0,2	3, 5, 6, 7	0
12	1150	8	0

Table 4. Characteristics of transport means

Parameter	Unit	u = *1*	u = *2*	u = *3*	u = *4*	*u* = 8
$t_{maxr}(u)$	*K*	*330*	*278*	*278*	*320*	280
$t_{minr}(u)$	*K*	*255*	*273*	*274*	*255*	268
$\varphi_{maxr}(u)$	*%*	*90*	*95*	*95*	*96*	100
$\varphi_{minr}(u)$	*%*	*40*	*90*	*94*	*50*	90
$\Delta t_{rz}(u)$	*K*	*40*	*1*	*1,2*	*40*	12
$\Delta\varphi_{rz}(u)$	*%*	*50*	*3*	*4*	*5*	5
$w(u)$	-	*1*	*0*	*0*	*0*	0
$\phi(u)$	*μl/kg*	*0*	*4800*	*3450*	*0*	1230
$w_{ux}(u)$	*m*	*13,2*	*12*	*2*	*8*	12
$w_{uy}(u)$	*m*	*2,5*	*2,4*	*2*	*2*	2
$w_{uz}(u)$	*m*	*2,67*	*2,4*	*2*	*2*	2
$w_{uxp}(u)$	*m*	*0,4*	*0,8*	*0,4*	*0,15*	2
$w_{uyp}(u)$	*m*	*0,2*	*0,4*	*0,6*	*0,15*	2
$w_{uzp}(u)$	*m*	*0,3*	*0,3*	*0,3*	*0,15*	2
$Q_{dop}(u)$	*kg*	*17500*	*16000*	*3500*	*800*	14000
$V_{dop}(u)$	m^3	*88,11*	69,12	8	32	48
$k_{ts}(u)$	PLN/km	12	14	15	24	12
$k_{tt}(u)$	PLN/h	3	44	17	22	8
$f_{u1max}(u)$	N/m^2	10	8	17	22	14
$f_{u1maxd}(u)$	N/m^2	14	12	22	18	17
$ow_u(u)$	-	1	1	1	1	0
$os_u(u)$	-	1	1	1	1	1
$UU(u)$	-	3, 5, 6, 7	3, 5, 6, 7	3, 5, 6, 7	3, 5, 6, 7	3, 5, 6, 7
$P_{U1}(u)$	-	1, 2	1, 2	1, 2	1, 2	1, 2
$LSP(u)$	-	1	1	1	1	1

Moreover, characteristics of various types of cargo, such as external dimensions, resistance to mechanical damage, value of temperature and humidity and the possibility to regulate to a certain extent, were identified.

Table 5. Characteristics of loading devices

Parameter	Unit	*u* = 3	*u* = 5	*u* = 6	*u* = 7
$F_Q(u)$	kg	4500	4200	4000	3300
$W(u)$	kg/h	1200	555	400	500
$g_t(u)$	-	0,55	0,55	0,58	0,66
$k_{j2}(u)$	PLN/h	13	12	11	13
$f_{u2max}(u)$	N/m^2	10	10	14	32
$f_{u2maxd}(u)$	N/m^2	43	44	73	22
$w_{u2x}(u)$	m	2	1	4	5
$w_{u2y}(u)$	m	3	1	4	5
$w_{u2z}(u)$	m	2	1	4	5
$w_{u2xp}(u)$	m	1	0,8	1,2	1
$w_{u2yp}(u)$	m	1	1,2	1,2	1
$w_{u2zp}(u)$	m	1	0,5	1,2	1
$\boldsymbol{P}_{U2}(u)$	-	1, 2	1, 2	1, 2	1, 2
$\boldsymbol{LSP}(u)$	-	1	1	1	1

4.3. Solution to the problem along with multicriteria assessment

In the first stage of calculations, the selection of labor sources and workers was carried out for the following steps foreseen in terms of various variants of the technological process. This selection was completed in such a way that the safety criteria calculated for the entire technological process assumed the greatest value and the criterion of cost minimization assumed the lowest value. The value of the target function determined for each technological solution is presented in Table 6.

Due to the fact that for the fourth type of transport technology, one of the cargo safety criterion assumes a value equal to zero, this technology is not considered in further solutions, such as multicritera assessment of technological variants, since it has an unacceptable solution.

The multicritera assessment was conducted using the multicriteria method MAJA (Jacyna, 2001). In the examined case, the safety criteria, i.e. 0,027(7) was assumed to have identical weight, however, the economic criterion was weighted 0,5**. Safety criteria are maximized, whereas the economic criteria are minimized. According to the method of multicriteria assessment, a normalization of assessments was carried out, and next the values for conformity matrixes were determined **Z** (tab. 7) as well as nonconformity matrices **N** (tab. 8).

Table 6. Values of partial criteria for each technological variant

Criterion	Notation	*d* = 1	*d* = 2	*d* = 3	*d* = 4
Maximum air temperature directly surrounding cargo	$F1_1(\boldsymbol{X})$	0,00248	0,00674	0,00674	0,00248
Minimum air temperature directly surrounding cargo	$F1_2(\boldsymbol{X})$	1,00000	1,00000	0,36788	1,00000
Air temperature fluctuations directly surrounding the cargo	$F1_3(\boldsymbol{X})$	0,75000	0,75000	0,75000	0,75000
Maximum humidity directly surrounding the cargo	$F1_4(\boldsymbol{X})$	1,00000	1,00000	1,00000	1,00000
Minimum humidity directly surrounding the cargo	$F1_5(\boldsymbol{X})$	1,00000	1,00000	1,00000	1,00000
Humidity fluctuations directly surrounding the cargo	$F1_6(\boldsymbol{X})$	0,41667	1,00000	1,00000	0,55556
Volume of emitted ethylene	$F1_7(\boldsymbol{X})$	1,00000	1,00000	0,22727	1,00000
Sensitivity to the effects of ethylene	$F1_8(\boldsymbol{X})$	1,00000	1,00000	0,22727	1,00000
Requirement of applying a modified atmosphere directly surrounding the cargo	$F1_9(\boldsymbol{X})$	1,00000	1,00000	0,50000	1,00000
Resistance of cargo to mechanical damage caused by static forces	$F1_{10}(\boldsymbol{X})$	0,63212	1,00000	1,00000	0,99967
Resistance of cargo to mechanical damage caused by dynamic forces	$F1_{11}(\boldsymbol{X})$	0,99967	1,00000	1,00000	0,99999
Acceptable transport time	$F1_{12}(\boldsymbol{X})$	0,10636	0,31515	0,30606	**0,00000**
Maximum cargo dimensions	$F1_{13}(\mathbf{X})$	0,60000	0,60000	0,60000	0,60000
Preferential dimensions of cargo	$F1_{14}(\mathbf{X})$	0,20000	0,17647	0,17647	0,20000
Use of carrying capacity (mass)	$F1_{15}(\mathbf{X})$	0,86250	0,69000	0,69000	0,86250
Mass of unit load or packaging unit along with cargo	$F1_{16}(\mathbf{X})$	0,51000	0,51000	0,51000	0,51000
Volume of unit load or packaging unit along with cargo	$F1_{17}(\mathbf{X})$	0,99960	0,99875	0,99875	0,99960
Cargo value	$F1_{18}(\mathbf{X})$	0,78114	0,71035	0,43344	0,00157
Transport cost	$F2(\mathbf{Y}, \mathbf{Z})$	22052	21702	24045	22900

Table 7. Elements of conformity matrix **Z**

	d = 1	*d* = 2	*d* = 3
d = 1	0	0,11111	0,72222
d = 2	0,63889	0	0,66667
d = 3	0	0	0

Table 8. Elements of non-conformity matrix **N**

	d = 1	*d* = 2	*d* = 3
d = 1	0	0,85735	0,82002
d = 2	0,25882	0	0
d = 3	1	1	0

In the next step, for the given values of the compliance threshold $pz = 0,6$ and non-compliance threshold $pn = 0,4$, a dominance matrix was set and a dominance graph was constructed on its basis (Fig. 3).
Based on the dominance graph, it has been observed that the best technological variant for the completion of the analyzed transportation task is transport technology *d* = 2. This means that in order to carry out the transportation task, the multimodal transport technology which includes road and railway transport with transshipment in the transshipment terminal B should be used.

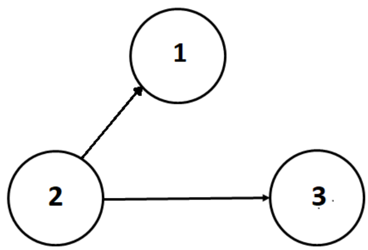


Fig. 3. Dominance graph **G**

5. Conclusions

The developed model for selection of multimodal transport technologies of perishable products forms the basis of the selection method of these technologies. This method is a practical tool for the selection of transport technologies for given transportation tasks. In the developed method, depending on the considered problem (including characteristics of cargo and their packaging forms – types of cargo), the appropriate elements are considered in the mathematical model described in the article. For a significant group of perishable cargo, it is not required to consider all defined criteria associated with cargo safety.
Selection of technologies is carried out based on cargo transportability coefficients identified based

on a series of criteria regarding the safety of transported cargo, including, among others, acceptable transport time, maximum and minimum air temperature, cargo dimensions and resistance to mechanical damage. As a consequence, aside from minimizing transport costs, it is possible to maximize the safety of transported cargo. It is important to emphasize that, technological solutions which application may negatively impact the transported cargo are eliminated from the set of acceptable solutions thanks to the developed constraints.
If, for a given variant, any of the criteria associated with cargo safety assumes a value equal to zero, the variant is an unacceptable solution and is not considered in the multicriteria assessment, which allows for the limitation of calculations and simplifies the problem.
Application of the developed model and method allowed for the selection of a transport technology variant while considering a multicriteria approach. For the example discussed in the article, the best solution was determined by considering 19 partial criteria- 18 associated with transportability and cargo safety, as well as one criterion regarding transport cost.
In terms of further research, it is possible to develop this method further through considering additional characteristics of perishable cargo. Nevertheless, the developed model in its current form allows for the correct selection of cargo transport technology of perishable products for most transportation tasks. Along with this, it is also possible to select single-branch and multimodal technologies, as well as compare the two.

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