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VALUE OF TIME AND VALUE OF RELIABILITY FOR FREIGHT TRANSPORTATION IN INDONESIA

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Abstract: *Value of Time (VOT) is an important value for designing and evaluating transportation network because of its part in generalized cost, which also closely related to the Value of Reliability (VOR). However, since studies on freight transport in Indonesia have received less attention compared to passenger transport, the updated data of VOT and VOR for freight transport were unavailable. Therefore, this study attempts to determine the VOT and VOR for freight transport in Indonesia. In order to estimate those values, data collection was carried out with stated preference surveys for shippers, carriers, and freight forwarders. Utilizing 33 samples that were successfully collected amidst the difficulties of conducting surveys during COVID-19 pandemic, VOT and VOR were estimated using the logit model. Based on the survey results and calculations, the average VOT for truck is about $9.56 per shipment per hour, and sea is about $5.57 per shipment per hour, whereas the average VOR for truck is about $67.83 per shipment per hour, and sea is about $25.21 per shipment per hour. These results also indicate that reliability holds significant role in freight transport in Indonesia.*

Keywords: *Value of Time (VOT), Value of Reliability (VOR), Freight Transportation*

Introduction

Indonesia is an archipelagic country which has 5 big islands and more than 17,000 other islands. Within this condition, the provision of effective and efficient freight transportation is challenging. In addition, the imbalance of infrastructure development among regions also exacerbates this condition.

The overall position of Indonesia's Logistics Performance Index (LPI) was ranked 46 out of 160 countries, below other ASEAN countries such as Singapore (7), Thailand (32), Vietnam (39), and Malaysia (41). This is caused by inadequate infrastructure support, both in terms of quantity and quality - which is not managed in an integrated, effective, and efficient manner-, also ineffective multimodal transportation and interconnection between port, warehousing and transportation infrastructure (Wirabrata and Silalahi, 2012). Low efficiency in some collection and distribution nodes has also caused high cost and high operating time of transportation systems that affected the service's performance and mobility which in turn, will also affect its service capacity (Lubis et al, 2005).

Especially multimodal transportation of goods (which involves at least two freight modes), controlling the overall network performance is difficult, because it is a combination of various modes which has different cost, time, and reliability values. Multimodal freight transport networks could likewise support the economic development of cities, regions, and countries, and help reduce negative impacts on the environment and energy consumption (Yamada et al, 2009). To make multimodal transportation concepts more attractive and desirable than road transport, generalized transport cost should be equal or lower (van Klink and van den Berg, 1998).

Generalized transport costs are the sum of monetary costs (elements) and non-monetary costs (elements) of a journey (Grosso, 2011). The non-monetary costs can be calculated through the number of qualitative attributes that are not immediately valuable with a monetary index, but play an important role in freight transportation, such as VOT in relation to the urgency of the delivery, the reliability of a safe and on time journey, impact on the environment, etc. (Grosso, 2011). Furthermore, VOT and VOR are crucial for converting the impacts of transport projects into monetary unit (de Jong et al, 2014).

Compared to the transportation of people/passengers, VOT for freight transportation receives less research attention because it involves a large number of decision makers, a complicated negotiation process, and limited data (Tao and Zhu, 2020). This study attempts to fill that discrepancy, to determine the VOT and VOR for freight transportation in Indonesia.

Literature Review

Tao and Zhu (2020) define the VOT in freight transportation as monetary value that decision makers (e.g., carriers and shippers) are willing to pay to reduce transportation time when moving goods from origin to destination, Tamin (2008) define the VOT as the amount of money a person makes available (or saved) to save one unit of travel time, and Morisugi (2016) define it as the marginal substitution rate between price and time and expressed it as the freight service fee per freight time multiplied by the elasticity of quantity level indicator with respect to freight time.

Reliability has been defined in several heterogeneous ways by the authors that have considered this transport quality attribute (Zamparini et al, 2011). Travel time reliability intends to measure the unexpected deviation from the expected duration of travel, which travelers develop through their travel experiences or from external sources (Shams et al, 2017). In general, there are three approaches that commonly used to represent reliability measures in freight studies, namely the scheduling-based approach (represents the probability or duration of early or late arrival from the scheduled time of arrival), the mean-variance-based approach (represents the variation, i.e., standard deviation, of the in-transit time), and the on-time delivery-based approach (represents the probability of on-time delivery) (Shams et al, 2017). This research applied mean-variance-based approach.

Table 1 shows summary of selected previous research, with the number of samples, location, and the attributes considered in the analysis.

Table 1: Summary of Selected Previous Studies

Studies	Location	Sample Size	Attributes
Small et al (1999)	US	20	Travel time, travel cost, reliability
Kurri et al (2000)	Finland	172	Travel time, travel cost, reliability
Wigan et al (2000)	Australia	43	Travel time, reliability, damage
Bolis and Maggi (2003)	Italy, Switzerland	22	Travel time, travel cost, reliability, frequency
Gong et al (2012)	US	24	Travel time, travel cost, reliability
De Jong et al (2014)	Netherlands	812	Travel time, travel cost, reliability, arrival time
Shams et al (2017)	US	150	Travel time, travel cost, reliability

Stated Preference Survey

Stated preference (SP) was used to collect data and information through individual interviews for hypothetical conditions regarding various scenarios and alternatives. Given the different characteristics on each island, hypothetical conditions were defined to minimize extreme variations in respondents' answers. Jakarta-Surabaya delivery was chosen as one of hypothetical condition.

Previous research (Small, 1999, Halse et al, 2011, Gong et al, 2012, etc) was also conducting stated preference survey to collect data for the estimation. Whereas other research (Fowkes et al, 2004, and Shams et al, 2017) was using stated preference survey methods that take advantage of computers with choice sets that adjusted based on the respondent's answer, known as computerized adaptive stated preference.

The SP survey was conducted in 3 different methods, namely CASI (computer-assisted self-interview), PAPI (pen and paper interview), and CATI (computer-assisted telephone interview). These methods were selected by considering limited time, conditions, number of respondents, and availability of the resources. Some of the challenges faced are due to the COVID-19 pandemic situation which hampered permits for PAPI surveys, while CASI and CATI also received a low response rate. However, various ways have been done to increase the response rate and produce the best results.

The target respondents in this interview are mainly decision makers in freight transportation. Carriers are in the best position to give VOT related to the cost of providing transportation services, while shippers are most interested in the VOT that is related to the goods themselves (de Jong et al, 2014). Freight forwarders are also included as respondents, where some classify the freight forwarder as a "contractual carrier".

Previous researches were used as initial references for designing the questionnaire. One of the most important things in a preference survey is that the respondent must understand the question and the available options well.

Questionnaire for this SP survey consisted of 3 main parts:

1. Questions related to the identity of the respondent
2. Questions related to travel inquiries
3. SP survey in the mode itself.

The selected attributes used in the SP survey were based on the literature review that have been conducted, namely:

1. Travel cost from origin to destination (door to door)
2. Travel time from origin to destination (door to door)
3. Reliability (standard deviation of travel time).

Different attribute levels were created for each of these three attributes. The level setting for travel costs and travel time consists of three levels: one level of existing value, one level lower than the existing value, and one level higher than the existing value. The reliability attribute also has three levels, but with low, medium, and high levels setting. Level for reliability is based on the study conducted by Shams et all (2017) and Small (1999), with some modifications and adjustments, according to existing conditions of travel time. All attribute level will also vary depending on the freight mode used by the respondents. Truck in this research refers to road transport, and sea refers to sea transport which is a combination of truck and ship.

Table 2: Attribute Level for Reliability

Mode	Low Reliability	Medium Reliability	High Reliability
Truck/Road	80% shipment late 4-6 hours	60% shipment late 2-4 hours	20% shipment late 2 hours
Sea	80% shipment late 2-3 days	60% shipment late 1-2 days	20% shipment late ½ day

After the attributes and attribute levels were formed, the next step was combining the attributes and attribute levels to form choice set. First, orthogonal experimental design was used, so that the original $3^3 = 27$ combinations when using the full factorial design were reduced to 9 combinations. Based on the several methods that can be used to create choice set, the sequential choice sets creation method is selected with the shifting approach. However, sometimes it will be formed when one alternative is more dominant than other alternative, so it is necessary to adjust one/more of the attribute levels to ensure that there is no dominant alternative.

Figure 1 shows an example of a question in a stated preference survey that presents two alternatives for each question.

Which alternatives is better?				
Alternative	Transport Cost	Transport Time	Reliability	Answer
A	2 million higher than existing	same as existing	60% of the shipments about 2-4 hours late (Medium reliability)	
B	2 million lower than existing	5 hours slower than existing	20% of the shipments about 2 hours late (High reliability)	

Figure 1: Example of Question with Two Alternatives

Sample Characteristics

Analysis was carried out by utilizing 33 samples that were successfully collected amidst the difficulties of conducting surveys during COVID-19 pandemic (May-June 2021). Table 3 shows a statistical characteristic of the sample. By the cooperation with logistics and freight forwarder associations, samples were fulfilled with freight forwarder made up most of the sample. As for the commodities, most of them are agriculture, plantation, and consumer goods.

Table 3: Statistical Characteristics of the Sample

Parameter	Frequency	Percentage (%)
Main Mode		
Truck/Road	22	66.7
Sea	11	33.3
Respondent Type		
Shipper	10	30.3
Carrier	8	24.2
Freight forwarder	15	45.5
Commodity Type		
Construction materials, furniture	5	15.2
Agriculture, plantation, consumer goods	11	33.3
Spare parts, electronics, machinery	5	15.2
General cargo / mixed	3	9.1
Paper, textiles	4	12.1
Others	5	15.2

From three attributes presented in each alternative in the SP survey, namely travel cost, travel time, and reliability, it is interesting to see if respondents will always choose the fastest travel time or the cheapest travel cost. For this reason, a simple analysis was carried out to find out the respondents' answers regarding this matter. Of the 33 respondents, 15.2% respondents always choose the cheapest alternative. Meanwhile, there are no respondents who consistently always prioritize travel time or fastest options in available alternatives given.

Table 4 Statistical Characteristics of Respondents' Choice

Alternative Scenario	Percentage (%)
Always choose the cheapest alternative	15.2
Always choose the fastest alternative	0

Modelling

One of the popular methods used to estimate VOT and VOR in previous research is the logit models. Logit models are stochastic discrete choice model, based on random utility theory, that make use of the theoretical construct of utility (Kurri et al, 2000). Shams et al (2017) utilized two different logit models, multinomial logit (additive and multiplicative utility specification) and mixed logit. Additive utility specification was adapted for this study.

$$U = \beta_C * C + \beta_T * T + \beta_R * R + \varepsilon \quad (1)$$

where:
β_C = coefficient for travel cost
β_T = coefficient for travel time
β_R = coefficient for reliability
C = travel cost
T = travel time
R = reliability (standard deviation of travel time)
ε = random error

So that the VOT and VOR can be obtained by:

$$\text{VOT} = \beta_T / \beta_C \quad (2)$$
$$\text{VOR} = \beta_R / \beta_C \quad (3)$$

Result

After getting the calculation results by forming a utility function with a logit model, the first thing to ensure is all coefficients must be negative. Smaller travel cost, travel time, and standard deviation of travel time should make utility higher, which means that the alternative is better. In other words, without a negative coefficient for initial calculation, there is no need to take additional steps to analyze the cause of the occurrence. This positive sign can occur because the freight transportation is a complicated matter.

Table 5 shows VOT and VOR for freight transportation, derived from models that estimated separately for each mode. It is important to note that dataset for travel cost was in million rupiah, so that the calculation for VOT and VOR should be multiplied by million rupiah after getting the coefficient. All values for VOT and VOR in this research are per shipment.

Table 5: Model Result

Parameter	Truck/Road	Sea
Constant alternative 2	-0.19552	0.23242
Travel cost	-0.39441	-0.10431
Travel time	-0.05444	-0.00839
Reliability	-0.38637	-0.03798
Value of time (Rp/h)	138,029	80,433
Value of reliability (Rp/h)	979,615	364,107
Value of time ($/h)	9.56	5.57
Value of reliability ($/h)	67.83	25.21

The average VOT for truck/road transport is about $9.56 per shipment per hour, and sea transport is about $5.57 per shipment per hour, whereas the average VOR for truck is about $67.83 per shipment per hour, and sea is about $25.21 per shipment per hour. Valuation of VOT and VOR were much higher for truck than in sea transport. This means that the parties involved in shipping by truck are more willing to pay more than the sea transport to reduce travel times, as well as to reduce the standard deviation of travel times. However, what should be noted is that the formed values are from a stated preference survey within the mode itself. The within-mode valuations should better reflect the valuations of decision makers, but not possible to use the models for any mode-choice analysis (Kurri et al, 2000).

Findings that is quite interesting is the VOR which is far above the VOT. Reliability ratio (Reliability ratio = VOR/VOT) is about 7.10 for truck and 4.53 for sea. This condition occurs because of the dominant commodities such as agriculture, plantation, and consumer goods, which are perishable commodities. Other possibility, this condition indicates that reliability holds very important role in freight transport in Indonesia.

VOT and VOR per shipment in previous research showing variation in values. In addition, it also shows the variation of the relationship value between VOT and VOR. However, the value obtained quite comparable and reasonable compared to previous research (Small et al (1999), Kurri et al (2000), Bergvist (2001), Gong et al (2012), Shams et al (2017)), which varied from $4.66 to $261.08 (adjusted to 2020 US$) per shipment per hour for VOT, whereas values from this research about $5.57 and $9.56 per shipment per hour. VOR value from previous research varied from $17.79 to $579.12 (adjusted to 2020 US$) per shipment per hour, whereas values from this research about $25.21 and $67.83 per shipment per hour.

Conclusion

Based on the survey results and calculations, the average VOT for truck is about $9.56 per shipment per hour, and sea is about $5.57 per shipment per hour, whereas the average VOR for truck is about $67.83 per shipment per hour, and sea is about $25.21 per shipment per hour. These results also indicate that reliability holds very important role in freight transportation. The results of the VOT and VOR obtained are quite reasonable compared to other studies also when compared between modes. However, this value is greatly influenced by the commodities delivered.

Future opportunities to enrich this study can be done by increasing the number of samples. COVID-19 pandemic gives a huge impact on data collection. Respondents are hesitant to be interviewed face to face through the PAPI method, while CASI and CATI method get a low response rate. Some other steps that can be taken to enrich this study are by adding other variables, using other utility functions or another modelling approaches to get the best results.

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IDENTIFICATION OF VORTEX STRUCTURES IN A COAXIAL JET

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Abstract: *This work examines some methods used to identify vortex structures in a coaxial compressible jet flow simulated by the 3D model (LES). The majority of these methods focus on the definition of vortices. The delta-criterion, lambda2-criterion, Q-criterion, and omega-criterion methods are considered among the most common local Eulerian vortex identification methods, based on local point analysis velocity gradient. Moreover, the delta-criterion, lambda2-criterion, and Q-criterion, vortex identification methods require selecting an appropriate criterion threshold. In contrast, the new Omega method can capture both strong and weak vortices without adjustment. Acomparative study of the different vortex identification methods was carried out to use the criterion that seems to be the most appropriate for the case study. The results show that the omega criterion identifies vortex structures more accurately than the other criteria.*

Keywords: *Large Eddy Simulation, coaxial, jet, Delta criterion, Q criterion, lamda2, omega.*

Introduction

Coaxial jet flows have been the subject of much research, both experimental and numerical. They contain vortex structures that play a major role in mixing and transfer. These vortex structures are often referred to as “coherent”. The search for a definition of a coherent structure has led to the development of methods for detecting vortex structures inflows. These methods allow us to better understand the mechanisms present in the flow and characterize the structures’ dynamics to plan a possible control process to optimize their influence. This is very useful for heat and mass transfer applications.

Lugt [1] gave an intuitive definition of a vortex structure as the rotational motion of several particles around a common center. This definition is questionable because it raises the question of the convection of the coherent structure in a flow. Indeed, it can only be correct for an observer moving with the coherent structure in the flow on the one hand. On the other hand, a local pressure minimum cannot detect a coherent structure and vice versa as demonstrated by Jeong and Hussain [2]. The vorticity tensor, being Galilean invariant, appears to be the most natural choice for the identification of a coherent structure.

Hussain [3] defined a coherent structure as a turbulent flow region whose instantaneous vorticity is correlated with the flow phase. According to the author, the identification of a coherent structure must be based on vorticity. Jeong and Hussain [2] also used this definition, as did Kida and Miura [4]. Indeed, the authors proved that vorticity does not distinguish between shear and rotation of a vortex. Based on this observation, Jeong and Hussain [2] presented a new definition of a coherent structure using a minimum pressure condition at the centerof a structure as a starting point. The authors defined a coherent structure as a related domain associated with the two negative eigenvalues of the sum of the squared deformation tensor and the squared rotation tensor $S^2 + \Omega^2$. Thus, the eigenvalues are real and if λ_1, λ_2 and λ_3 are the eigenvalues with $\lambda_1 \geq \lambda_2 \geq \lambda_3$, the new definition is equivalent to $\lambda_2 \leq 0$ in the core of the coherent structure. Hence, the λ_2 criterion is widely used for the detection of coherent structures. Hunt et al. [5] identified coherent structures using the second velocity gradient invariant ∇u only; areas of the flow for which this invariant *Q* is positive are, for example, vortices. Invariant *Q* is positive are, forinstance, eddies. Chong et al. [6] showed that for flows with circular or spiral streamlines, the eigenvalues of ∇u are complex. These complex values correspond to a strictly positive discriminant Δ-criteria of the characteristic equation. Unlike vorticity, the *Q*-criterion, λ_2-criterion, and Δ-criteria have the advantage of discriminating rotations and pure shear. Pierce, Moin, and Sayadi [7] demonstrated that the *Q* and λ_2 methods couldprovide the same graphs when applied to DNS data if the iso-surface thresholds are chosen appropriately. A new method, called the Omega vortex identification method, has been developed by Liu et al. [8], which gives a more accurate mathematical definition of the vortex and is quite robust without the requirement of an appropriate threshold. In this study, it is proposed to apply the Δ-criterion, λ_2-criterion, *Q*-criterion, and Omega-criterion to characterize the vortex structures that result in the coaxial jet flow of compressible air, simulated by the LES model. These criteria were used on the instantaneous velocity field to test the effectiveness of each of them.

Method of resolution

Δ Criterion

It is possible to define the vortices from the velocity gradient tensor (∇u). Chong et al. [6] showed that for flows with circular or spiral-shaped streamlines, the eigenvalues of (∇u) are complex. Thus, we have the characteristic equation for this tensor:

$$\sigma^3 - P\sigma^2 + Q\sigma - R = 0 \quad (1)$$

where *P*, *Q* and *R* arethe three ∇u invariants defined by:

$$P = \frac{\partial u_i}{\partial x_i} Q = \frac{1}{2}\left(\left(\frac{\partial u_i}{\partial x_i}\right)^2 - \frac{\partial u_i}{\partial x_j}\frac{\partial u_j}{\partial x_i}\right) R = det\left(\frac{\partial u_i}{\partial x_j}\right) \quad (2)$$

The complex ∇u eigenvalues reflect a tendency for local rotation and a convergence of the streamlines, the presence of a vortex. These complex values correspond to a strictly positive discriminant Δ of Eq. (1). Strictly positive values (Δ > 0) therefore indicate the presence of a vortex. In the case of an incompressible flow,we have the divergence of the zero velocity:

$$P = \nabla \boldsymbol{u} = 0 \quad (3)$$

and the criterion Δ is expressed as follows:

$$\Delta = (Q/3)^3 + (R/2)^2 \quad (4)$$

Q criterion

Hunt et al. [5], on the other hand, identified coherent structures using the second velocity gradient invariant ∇u only; areas of the flow for which this invariant *Q* is positive constitute eddies, for example. This invariant can be obtained using Eq. (1), or by redefining Q from the deformation and rotation rate tensors, the symmetric and antisymmetric parts of the velocity gradient tensor. The strain rate tensor is written as follows:

$$\underline{\underline{e}} = \frac{1}{2}(\nabla u + \nabla u^{\mathrm{T}}) \quad (5)$$

and the rotation rate tensor:

$$\underline{\underline{w}} = \frac{1}{2}(\nabla u - \nabla u^{\mathrm{T}}) \quad (6)$$

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We then definite norms associated with these two tensors. The dissipation S^2 is defined as follows:

$$S^2 = 2\underline{\underline{e}}.\underline{\underline{e}} \tag{7}$$

and the vorticity modulus or enstrophy Ω^2 by:

$$\Omega^2 = 2\underline{\underline{w}}.\underline{\underline{w}} \tag{8}$$

The *Q*-criterion can then be written as the difference betweenthe two norms (within a factor of $\frac{1}{2}$):

$$Q = \frac{1}{2}(\Omega^2 - S^2) \tag{9}$$

This expression is equivalent to that of Eq. (2). The *Q*-criterion, measures a local equilibrium between two types of flow: solid rotation and pure deformation. Vortices in which winding (rotation) takes precedence over energy dissipation (pure deformation) will have a positive *Q*-criterion. Purely dissipative zones will be associated with a negative *Q*-criterion. The *Q*-criterion can also be related to the pressure. By taking the divergence of the Navier-Stokes conservation of momentum equation, the pressure equation is found, and the *Q*-criterion appears:

$$\frac{1}{\rho}\Delta p = \frac{1}{2}(\Omega^2 - S^2) = Q \tag{10}$$

Thus, if we have a zone with a strongly negative *Q*-criterion (stronger dissipation than the winding), we have a negative curvature for the pressure with the presence of a local maximum of pressure. Conversely, if we have a zone with a strongly positive *Q*-criterion (presence of a vortex), we have a positive curvature for the pressure with the presence of a local pressure minimum; we can then define a pressure criterion for the detection of vortices.

λ_2 criterion

Jeong and Hussain [2], having noticed the possible ambiguity of a simple local pressure minimum criterion for detecting a vortex, showed that it is possible to relate pressure minima to vortex structures in a systematic way. The authors started from the flow dynamics and study the gradient of Navier-Stokes's momentum equation, which decomposes into symmetric and antisymmetric parts. The symmetrical part is then written:

$$\frac{\partial e_{ij}}{\partial t} + \nu\frac{\partial^2 e_{ij}}{\partial x_k^2} + w_{ik}w_{kj} + e_{ik}e_{kj} = -\frac{1}{\rho}\frac{\partial^2 p}{\partial x_i \partial x_j} \tag{11}$$

The Hemissian pressure matrix $\frac{\partial^2 p}{\partial x_i \partial x_j}$ which appears contains information on the extrema of pressure. Indeed, a study of its eigenvalues allows us to know if we are dealing locally with a maximum, a minimum, or a col point for the pressure; in the search for a pressure minimum, two of the eigenvalues must be positive. In Eq. (11), the first term on the left represents unsteady (irrotational) stretching; the second term represents viscous effects. Thus, if one wants to quantifier the effects of winding, only one can stick to a study of the sum of the tensors $w_{ik}w_{kj}$ and $e_{ik}e_{kj}$sometimes noted as $\Omega^2 + S^2$. This tensor is symmetric and therefore has only real eigenvalues. Suppose we order these eigenvalues of Ω2+ S2: $\lambda 1 \geq \lambda 2 \geq \lambda 3$. In that case, we deduce the criterion on λ_2 to have a local minimum of pressure due to the winding:

$\lambda_2 < 0$ This criterion can nevertheless be adapted to certain situations, in particular incompressible [9] or near-wall [10], by taking a threshold different from 0 for λ_2.

Omega criterion

Liu et al.[8] proposed a further decomposition of the vortex has a rotational and a non-rotational part.$omega$ is a ratio of the trace of the anti-symmetric tensor squared to the sum of the traces for the symmetric and anti-symmetric tensors squared as follows:

$$omega = \frac{\Omega^2}{S^2+\Omega^2+\varepsilon} \tag{12}$$

By this definition,$omega$ is always between 0 and 1 since S and Ω are non-negative.If rotation is fairly dominant, then $omega$ is very close to 1, as a solid body. If the liquid has strong shear without rotation, then $omega$ is close to 0. A vortex is defined as a region where the rotation exceeds the deformation, $omega > 0.5$. The higher the value of $omega$, the faster the rotation in this region and vice versa.

Results and discussion

A series of time series calculations were performed for a compressible coaxial jet flow by the LES model [11]. The simulations were performed in a computational domain extending over $30D_p$ in the axial direction and $17D_p$ in the transverse y and z directions. $[L_x \times L_y \times L_z] = [30D_p \times 17D_p \times 17D_p]$. An initial double hyperbolic tangent velocity profile is defined at the domain entry to approximate the actual velocity profile of a coaxial jet. The mean velocity components in the y and z transverse direction are zero. Randomly generated disturbances are imposed on the y and z transverse direction. Upper and lower boundary conditions of the slip calculation domain have been prescribed. The domain's front and rear boundary conditions are periodic, and the boundary conditions at the exit of the domain are convective.Table 1 lists the main physical characteristics of the simulated jet.

Table 1: List of the main physical characteristics of the simulated jet.

$Ru=V_s/V_p$	0.7
D_p/D_s	2
T_p/Ts	2.7
M_s	0.57
Re_p	6.25×10^5
Ru_2	0.1

Code validation

We implemented the four methods delta-criterion, λ_2-criterion, Q-criterion, and $omega$-criterion on our coaxial jet flow case to evaluate the different vortex identification methods. We also examined the delta, λ_2, Q and $omega$ methods when the primary and secondary structures form in the coaxial jet transition phase. A convergence test was performed to demonstrate that the converging calculations are satisfying the experimental measurements. The mean development of a coaxial jet with a velocity ratio less than one seems very similar to that of a single jet. We proceed to compare the results of this simulation with those of the experimental results of Gutmark & Wygnanski [12] for a single jet.

Figure 1 and 2 provide the RMS axial and transverse velocity component profiles in fully developed region. The self-similarity state of the flow is obtained in this region, which indicates a good result of this simulation.

The RMS velocity of components profiles is plotted with the profile obtained by Gutmark & Wygnanski [12]. A very good agreement is observed between these profiles.

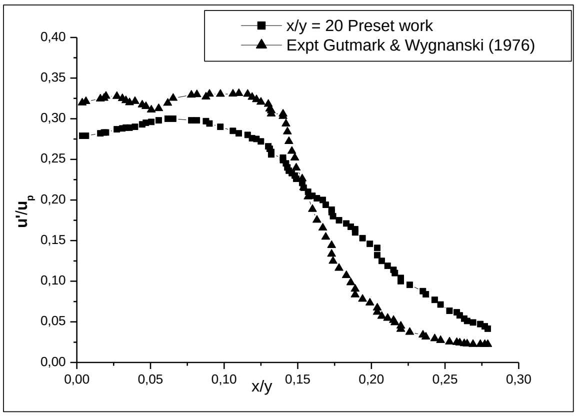

Figure 1: RMS axial velocity profile

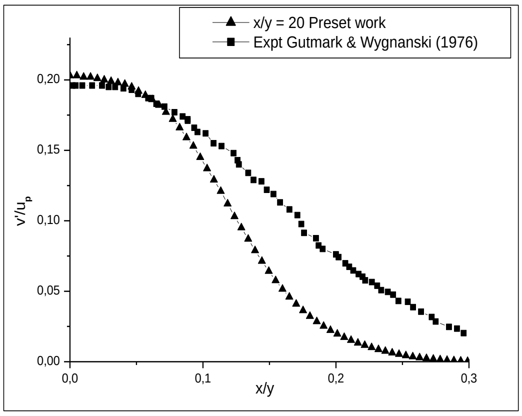

Figure 2: RMS transverse velocity profile

Figure 3 shows the Reynold'tension **ùv̀** profile. Reynolds tensions opposite in sign indicate the presence of the coherent vortices with opposite directions of rotation. The expansion and interaction of these vortices with downstream distance is confirmed by the expansion and decrease of peaks in **ùv̀**profile. The shear stress Reynolds *ùv̀* component profile is plotted with the profile obtained by Gutmark & Wygnanski [12]. A very good agreement is observed between the two profiles.

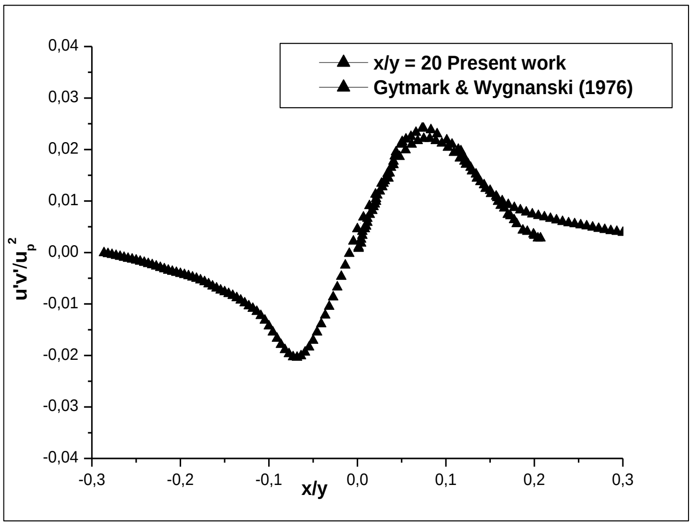

Figure 3: Shear stress Reynolds *ùv̀*

Figure 4 is a graphical representation of vortex structures detected by the different criteria delta, λ_2, Q and *omega*. It can be seen that all criteria correctly detect the vortex structures also the centres of these structures. The four methods have a great similarity in the identification of global vortex structures, but there are still differences in the local areas. It can be noted that the longitudinal vortices connect the outside of the upstream ring with the inside of the downstream ring, which has the effect of accelerating the vortex winding.

It can also be seen that the vortex structures are almost the same based on the Q-criteria and the λ_2-criteria. Indeed, these two quantities are related by $Q = -1/2\ (\lambda_1 + \lambda_2 + \lambda_3)$. This means that if Q has a positive value, the mean eigenvalue of λ_2 is most likely negative, and vice versa.

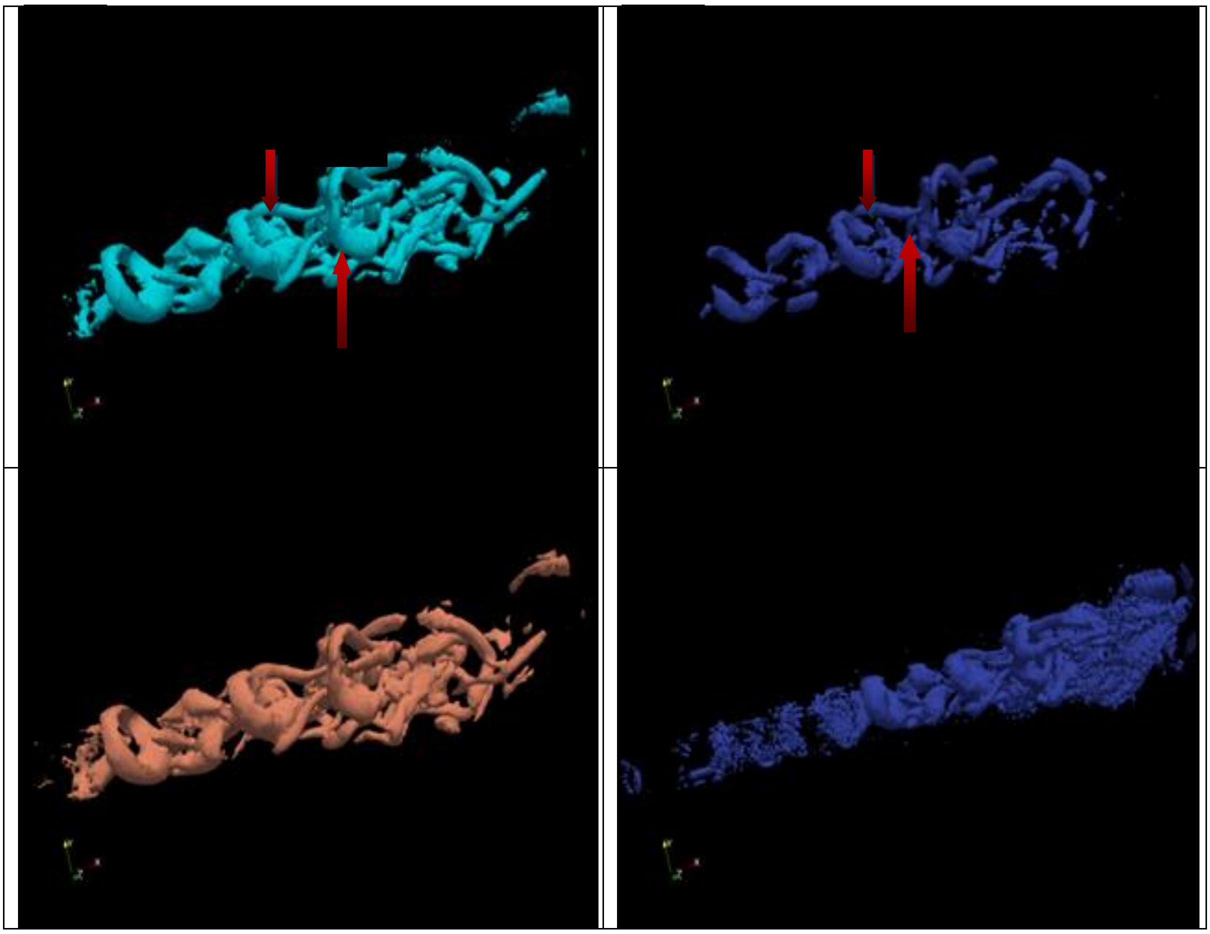

Figure 4: representation of vortex structures detected by the different a) Q-criteria, b) delta-criteria, c) λ_2-criteria, d) omega-criteria

Figure 5 shows the vortex structures given by the iso-surfaces of λ_2 = -0.03 and λ_2 = -0.01 in a time step t = 99000. Figure 6 shows the iso-surfaces of Q = 0.03 and Q = 0.01 at the same time step. Figure 7 shows the iso-surfaces of delta = 0.03 and delta = 0.01 at the same time step.

However, if we adjust the threshold as shown in figures 5 (a), 6 (a) and 7 (a), we can clearly see the main and secondary vortex structures and it is also seen that these structures are well stable. From figures 5, 6 and 7, the problem is to choose the right threshold for the three criteria that allows us to capture the vortex structures in a precise way.

It is sometimes difficult to choose an appropriate threshold for the λ_2, Q and delta methods. The choice of the threshold relies on the correct identification of the primary and secondary eddy structures. Figures 5 (b), 6 (b) and 7 (b) give a poor representation of the vortices.

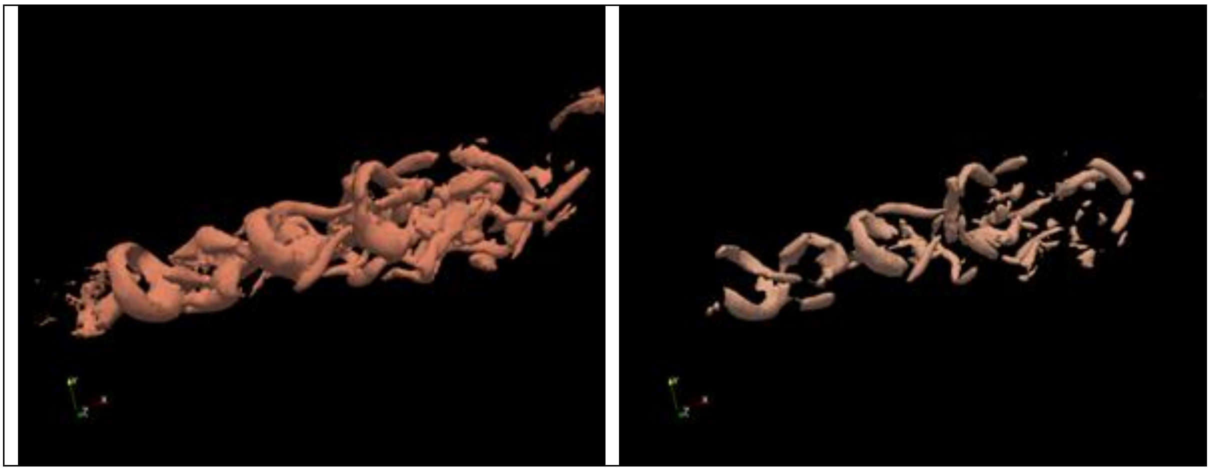

Figure 5: Iso-surfaces of λ_2-criteria a) λ_2 = -0.03, b)λ_2 = -0.01

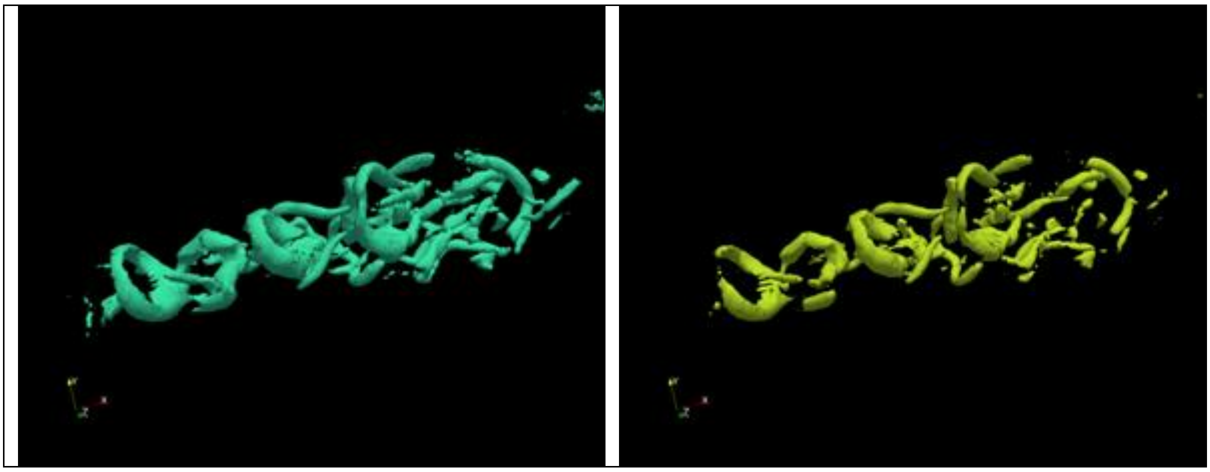

Figure 3: Iso-surfaces of Q -criteria a) Q = 0.03, b)Q = 0.01

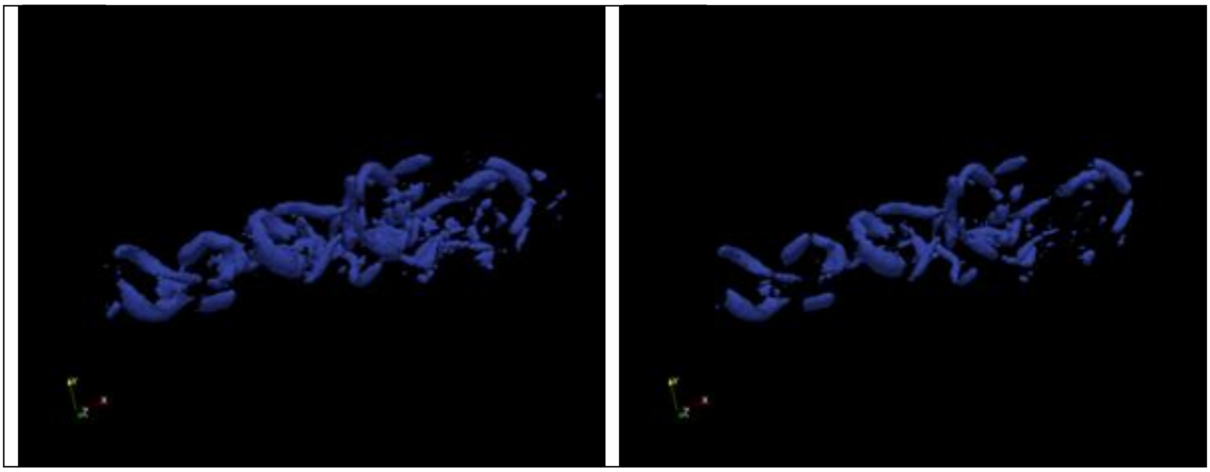

Figure 4: Iso-surfaces of delta-criteria a) delta = 0.03, b) delta = 0.01

Applying the Omega method, Figure 8 shows the iso-surface of omega = 0.52 at the same time step t = 99000. It can be seen that the vortex structures are well captured, with a fixed omega threshold equal to 0.52 without threshold adjustment.

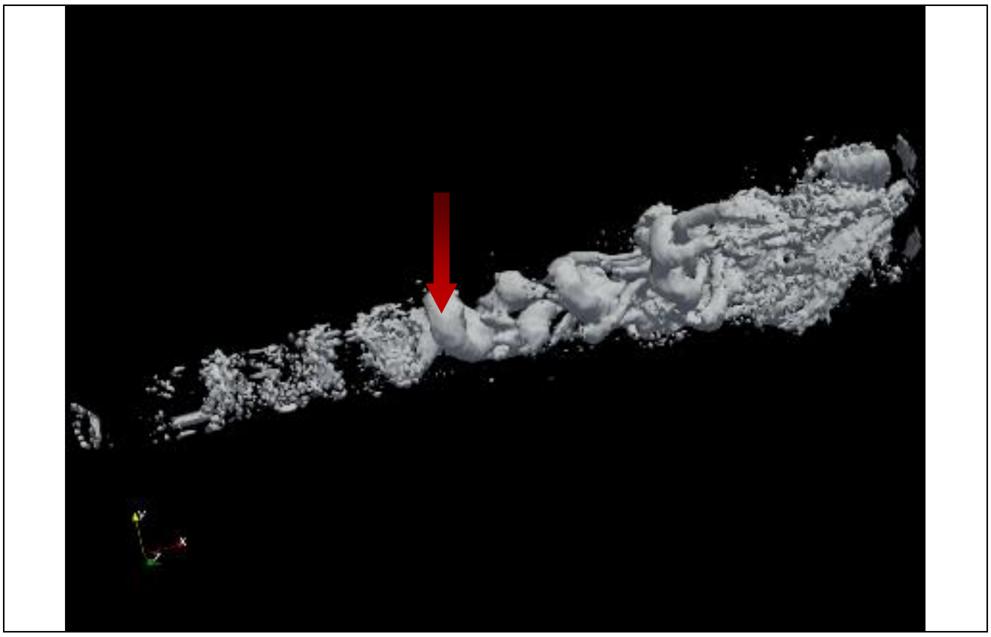

Figure 8: Iso-surfaces of omega = 0.52

after a number of threshold adjustments, figure 9 shows that the iso-surfaces: Q = 0.03, λ_2= -0.01, roughly capture the vortex structures and are similar to that in Figure 8.

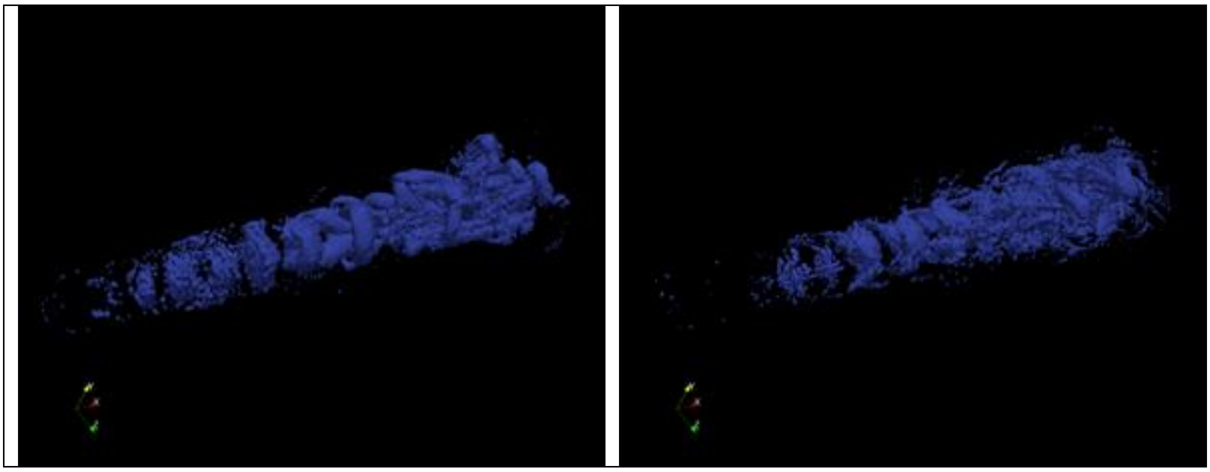

Figure 9:iso-surfaces$Q$-criteria and λ_2-criteria: a) Q = 0.03, b) λ_2= -0.01

Conclusion

There are many methods for detecting vortex structures to universally define coherent structures. The majority of these methods focus on the definition of vortices, yet none of them manage to give an objectively superior definition of them to the others. Therefore, it is appropriate in most cases to carry out comparative studies and use the criterion that seems to be most consistent with the observations of vorticity fields. We found that the Omega method can capture both strong and weak vortices without adjustment from the comparisons. There is no need to select an appropriate threshold, from time to time or even from region to region, so the Omega vortex identification method is valuable and useful for the study of the physics of turbulence and many other vortex-dominated flows.

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