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Effect of Inaugurating the Third Set of Locks in the Panama Canal on Vessel Size, Manoeuvring and Lockage Time

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The Panama Canal (PC) has recently been in the world spotlight. In August 2014, it celebrated 100 years of uninterrupted service and, in June 2016, the expansion project for the canal was inaugurated. The final project involved building a third set of locks. Once the canal started to operate, it could be seen that the way in which vessels transited the canal remained the same. However, the dimensions of locks and their revised operating procedures have had an effect on vessel size and the manoeuvres for the larger vessels. After the first transit on 26 June 2016, it was possible to have access to data on the new lockage systems for Neopanamax ships. The thorough statistical study of these new datasets (composed of Analysis of Variance (ANOVA), multivariate regression and statistical quality control techniques) has shown the main drivers of transit time across the Cocolí and Agua Clara locks. It has also made it possible to test the learning curve of Panama Canal pilots in the newly expanded canal. The effects of pilot training on the time it takes to transit through the locks, direction of entry in each lock, the type of vessel, vessel dimensions and the use of different types of manoeuvres have been analysed. The results are used to characterise and help optimise the performance of this new and unique lock system.

KEYWORDS

1. Panama Canal expansion project. 2. Lockage. 3. Statistical learning. 4. Statistical quality control. 5. Analysis of variance.

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1. INTRODUCTION. Just over a century ago, Huebner (1915) referred to the two main functions of the Panama Canal (PC). One was its military value, as it enabled the United States (US) to move naval vessels between the Atlantic and Pacific oceans. The other was its economic value; it offered a shortcut when freight was transported between the two oceans. The shortened distance directly reduced travel time, fuel costs and facilitated access to profitable markets. Huebner (1915) summarised the economic benefits of the PC to the US: the canal increased traffic, changed trade flows and stimulated both domestic and

international economies, along with the growth of industries. Therefore, while the canal's geographical position was first deemed crucial for strategic reasons (Sabonge, 2014), it had always played a role in the world of shipping.

The PC's operating system remained unchanged in 102 years of operation. However, there had been major changes in infrastructure and equipment. For example, the Culebra Cut was widened so that two Panamax vessels could transit the channel at the same time. Moreover, the waterways were illuminated and signalling was improved (Montero Llacer, 2005; Pagano et al., 2016). Nevertheless, the locks' dimensions had limited the size of the vessels that passed through them (Martin et al., 2015), to the point that a specific Panamax category was established for bulk carriers, tankers and container ships. This last category accounted for nearly 50% of the PC's transits before it was expanded (Pagano et al., 2016).

Subject to the principle of economy of scale, vessels have increased in size so that seaborne trade could become more competitive (Cullinane and Khanna, 2000; Stopford, 2009). As a result of this trend, a tripartite entity, comprising Japan, the US and Panama, was created in 1985 to look at options for the canal (Montero Llacer, 2005). Five alternatives were considered: a) widening the Culebra Cut, b) creating a centre-port, c) making a second sea level canal, d) building a third set of locks and e) establishing alternative systems of transport. However, as Cardoze (1991) and Montero Llacer (2005) pointed out, four of the solutions (b, c, d, and e) first entailed widening the Culebra Cut. This work was finished in 2001. It made it possible for a higher number of vessels to pass through the canal at the same time so that total transit time could be reduced (PCA, 2006a).

With four alternatives at hand, choosing one was a complex decision with political and technical implications. Exhaustive studies had to be carried out and consensus had to be gained between the Government and Panama's National Assembly (Montero Llacer, 2005). Montero (1990) outlines the reasons for building a third set of locks, including deadlines and budgets. Over time, this position best matched reality.

2. THE SOLUTION CHOSEN: EXPANDING THE CANAL.

Expanding the canal meant building a third set of locks larger than the ones made in 1914. A set of locks is located on the Atlantic side of the canal, on the east bank of the Gatun locks. Another set of locks is located on the Pacific side, to the southwest of Miraflores locks. The chambers of these new locks are 426.7 m long, 54.9 m wide and 18.3 m deep. To determine the dimensions of the locks' chambers, a vessel of certain dimensions served as a reference. This vessel had a length of 366 m, a beam of 49 m and a maximum draft of 15.1 m in tropical freshwater (PCA, 2006a, Ch. 6- P.18). Ungo and Sabonge (2012) stated that the reference vessel was a container ship designed to carry 13,200 TEU, given that this size of vessel would be the most likely to be used in the Asia to US East Coast trade. What became known as Post-Panamax vessels could then make use of the canal (PCA, 2006a, Ch. 6- P.20). Nevertheless, there is a possibility that the beam of these vessels would rise above 49 m to vessels designed to carry 14,100 TEU, once the locks' operating system had been perfected.

When it was time to choose the best types of gates for the new locks, it was decided that a sliding model was the most suitable (PCA, 2006a, Ch. 6- P.24). As was the case with the gates that had already been in use, new locks would have redundancy to allow for maintenance at each end of the chambers.

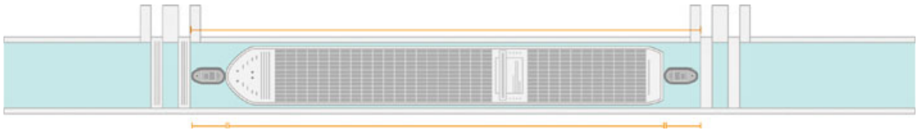

Figure 1. Layout of a lock in the expanded canal: with the location of the double sliding gates and the tugs in position. In the case of vessels whose length exceeds 1050 feet, the interior gates remain open to provide greater space.

A vital factor is how vessels are positioned along the lock chambers. Texas A & M University (1999) determined that "*no existing technology has been tested for the positioning of the ships by means of electromagnetic systems, involving devices like electromagnets or vehicles, with adequate capacity, safety and working levels to handle the dimensions of Post-Panamax vessels using the locks*". These systems had to be able to efficiently manoeuvre the Neopanamax vessels in the locks. At the same time, the systems had to be suitably flexible so that Panamax and a variety of smaller vessels could also transit through them. With these requirements in mind, two traditional systems were assessed: one, already in use, involving train engines, and another system in which tugboats were employed. This point is illustrated in Figure 1.

3. EFFECT ON MANOUEVRING THROUGH THE LOCKS.

3.1. *Options for positioning the vessel in the locks.* For handling the vessels that would pass through the locks, the Panama Canal Authority (PCA) assessed two options for when the expansion project would be in operation (PCA, 2006a, Ch. 6 P.26). One, involving locomotives, was similar to the system already in place. The second system would rely on tugboats, like the ones found in the post-Panamax locks in Berendrecht, Antwerp (Hensen, 2003; Port of Antwerp, 2016) The latter system is based on key technological developments in harbour tugboats (Carral Couce et al., 2015). The equipment needed for each option is very different; therefore the infrastructure and working guidelines would also vary enormously. The PCA (2006a) document proposed an analytical way to assess the two alternatives. It looked at factors such as the level of investment needed for the infrastructure and equipment. Moreover, it addressed the impact of water use and engineering and operational risks. Table 1 analyses these two alternative systems.

3.2. *Analysis of the alternatives.* In terms of investment costs, what is spent on acquisition and infrastructure would be lower if tugs were used. One might have thought that locomotives would have a lower initial cost than the tug system, but this was not the case (PCA, 2006a, Ch. 6 P.27). Vessels cannot be positioned just with locomotives. The system needs to be complemented with tugs to be effective; this is the way the canal works now. However, the extensive investment needed for this system's infrastructure would be spent on approach walls; cables can therefore be joined to the vessel before it comes into the lock chambers (PCA, 2006a, Ch. 6 P.26). Another expense is the traction-operated track rail that runs along the lock walls. These rails are not required with the tug system and investment costs are affected, as can be seen in Table 1.

For this reason, the report (PCA, 2006a, Ch. 6, P.26) estimated that 16 locomotives would be needed for a vessel with a 140,000 tonne displacement. This is equivalent to 32 locomotives per lock for relay operations. Five or six additional tugs are also needed at each lock, 10 or 12 throughout the whole complex. With the tug system, nine tugs would

Table 1. Analysing the alternative systems for positioning vessels along the locks. The comparison is based on a three-staircase lock that has a maximum beam of 49 m, length of 366 m and maximum depth of 15·2 m. It has sliding gates, but no basins for recycling the water. It would carry out an average of ten lockages each day, with potential demand being reached by around 2025 (PCA, 2006a, Ch. 6). Source: author's own based on PCA (2006a, Ch. 6)

Selection criteria	% weighting	Positioning with engines	value	Positioning with tugboats	value
Acquisition and investment costs	50	neutral	2·7	very favourable	5·0
Effects on water use	25	very favourable	5·2	favourable	3·6
Operational and technical risks	25	adverse	2	favourable	4·2
Total number of points	100		6·3		8·9

Table 2. Comparing the working and infrastructure requirements for both lock options. A positioning system that relies on train engines needs 16 engines for a vessel with a 140,000 tonne displacement and a working speed of 2 miles per hour. This is equivalent to 32 train engines and five tugs for each lock for relay operation. Source: author's own based on PCA (2006a).

	Tugs	Engines
Number of units in the locks	4-6	32
Number of additional tugs	6–4	5–6
Working crew	12	80
Approach wall	no	yes
Towing tracks, drivers and fenders	no	yes
Maintenance	6 units	37 units
Reconditioning	4 years	30 years
Other costs	fuel	electricity

be necessary for the Pacific and another eight for the Atlantic. This point is illustrated in Table 2. That means five or six fewer tugs from one system to the other, meaning a lower investment cost for equipment (PCA, 2006a, Ch. 6, P.27).

3.3. *Operation.* Two tugs - one at the bow and the other at the stern - help position the vessel inside the lock. In the case of Neopanamax vessels, up to three tugs are needed. Once the ship enters the lock chamber, it is immobilised while the lock is filled and drained. Here the mooring system comes into play with the help of linemen on board and along the lock walls (PCA, 2006a, Ch. 6 P.37). Once water levels in the chamber have equalised, the gates will be opened and the vessel will proceed to the next chamber. The process will then be repeated. Leaving the lock, the vessel will be detached from the tugs as soon as possible (PCA, 2006a, Ch. 6 P.37).

Within the chamber, the pilot can decide to centre the vessel. As the ship is moved between chambers, it can be kept equidistant from the lock walls. Inside the chamber, the pilot can then use the vessel's own rudder and the tug to move the vessel towards the side wall. The next step is to immobilise the vessel with breast lines and springs during lockage, while the chamber is being drained or filled. Once the gates have been opened, the tugs will have to bring the vessel back to the centre of the chamber to keep up with the movement. This Central/sideways operation mode is represented in the first row of Table 3.

A variation of this process entails centring the vessel in the chamber and then immobilising it in the same position by means of moorings along both sides. In this way, lateral movements are avoided, although the work of the linemen in the chamber is doubled. This

Table 3. Operational modes for the joint effort of tug and vessel inside the chambers with detailed description of the circumstances. (1) Manoeuvre procedure not applicable to cruise ships.

Manoeuvre type	Tugs	PCA crew on board and on lock	Critical points
Central-sideways (1)	Mostly active	Working 4 moorings	Tug activity
Central	Active whilst moving vessel	Working 4 moorings	Mooring activity
Sideways (1)	Active whilst moving vessel	Working 8 moorings	Vessel-fender interaction

method is compulsory for cruise ships. The central operation mode is illustrated in the second row of Table 3.

A second possibility is to have the vessel move sideways towards the side approach wall so that its flanks slide along the fenders running along the chamber walls. When the vessel is inside the chamber, it is brought to a halt with the combined action of its engines and the tugs. While the chamber is filled and drained, the ship is immobilised with the springs and crossbars of the mooring system. The doors then open and the pilot asks the tug operator to recover his position. Movement of the vessel is restored with the help of the tug and the ship's engines. This third operation mode, the sideways manoeuvre, is shown in the last row of Table 3.

4. EFFECT ON LOCKAGE TIMES – STATISTICAL ANALYSIS.

The PC's maximum sustainable capacity is limited by the physical and mechanical cycles of the locks' operation (PCA, 2006a). Moreover, the total lockage time is conditioned by the fixed factor of the locks' layout in reaction to the operating speed in which their chambers are filled and drained. There is also the interaction of other variables, including the efficiency of the assigned workers, weather conditions and a lock's operating system. Table 4 shows the time periods with the lockage activity broken down into sub-tasks.

Regarding pilot and pilot experience factors, transiting locks and channels has its own unique features; piloting the PC is a specialised task that requires great efficiency (Montero Llacer, 2005). The number of pilots has gone from 25 to 300, taken on to handle Neopanamax vessels after a period of training. A continuous series of training transits was carried out involving the bulk carrier *Baroque*, chartered by the PCA (Acosta, 2016). Not all pilots will be authorised to handle vessels of this size. For these vessels, the PCA specifies a specific level of experience in accordance with their dimensions, displacement and/or load (PCA, 2006b, Ch. 6, P.38). In any case, it is expected that two pilots will be carried for each full transit of Neopanamax vessels. Allowing for roster changes, an average of 2.5 pilots per transit will be required (PCA, 2006b, Ch. 6, P38).

Once inaugurated on 26 June 2016, the third set of locks started to operate. Balboa Maritime Traffic Control Center (Kimball and Shepard, 1962) monitored the manoeuvres of ships transiting the expanded canal. Consequently the PCA could carry out a census on the time vessels spent in the lock. 137 transits took place in the two month-long observation period. Taking into account that the vast majority of vessels correspond to container, Liquid Petroleum Gas (LPG) and Liquid Natural Gas (LNG) types, 130 transits corresponding to these types were studied, and tankers and vehicle carriers were omitted. The resulting dataset is composed of different critical variables during the lock transit process. These are the type of vessel, date, lock, transit direction (from north to south or vice versa), use of bow propeller, use of tandem manoeuvre, draft, difference of draft, length, beam, PC pilot,

Table 4. Time periods with the lockage activity broken down into sub-tasks. The locks pose two kinds of restrictions on canal capacity: one based on the time necessary for carrying out the lockage while the other corresponds with the chamber size of the locks. Dealing with the first of these, lockage times are defined according to the time it takes the gates to open and close; the gravity influenced movement of water through the pipes and lock chambers, and the time needed to move the vessel between chambers. The sum total of these factors determines lockage times.

		Operations by locks	
Component	Times	Cocolí	Agua Clara
Opening/closing of gate	5–7 min.	6–12	6–12
Filling/draining chamber	8–17 min.(1)	6	6
Moving vessel between chamber	10–20 min.	3	3
Mooring	10–20 min.	3	3
Boats entering and leaving	10–20 min.	2	2

(1) This will depend on whether or not water recycling basins are used.

and PC pilot experience (number of transits across each lock, irrespective of the direction of traffic). A comprehensive statistical analysis was performed and shown in this section to identify the most influencing factors and quantitative variables in the lock transit time, to model these dependence relationships, to estimate and control the time variability, and to evaluate the pilot learning effect over transit time (Carral Couce et al., 2016). Thus, this section is divided according to the statistical tools applied: firstly, exploratory analysis and Analysis of Variance (ANOVA) tests were performed, then statistical quality control was applied to transit times for each lock, and finally multivariate regression models were used to define the dependence relationship between transit time and their influencing parameters. The goal of this analysis was to identify the factors that determine lock transit time, in which way and to what extent. This will allow improvements to traffic management, and allow the taking of effective actions if changes in transit time are required. All the calculations are implemented using the free source statistical software R (Venables and Smith, 2008) and its packages ggplot2, relaimpo (Grömping, 2006), qcc (Strucca, 2004) and qcr (Flores et al., 2016).

4.1. *Statistical exploratory analysis and ANOVA study.* The goal is to obtain a primary description of transit time, its position, variability and how it is modified by the variation of other parameters such as direction of transit, type of vessel, pilot, number of manoeuvres or experience of pilots, among others. Identifying the factors that determine the value of lock transit time is the first step to estimating statistical regression models that define their dependence relationship.

Figure 2 shows that there are different transit times, with regard to position and dispersion, taking into account different types of vessels, transited lock and transit direction. The boxplots (with the addition of real observations in black) indicate that there are different median transit times with respect to the type of vessel in all the locks and in all directions. The median transit time of LNG is shorter than that of LPG and containers, while the time dispersion of containers is higher than the others (in addition, transit time for containers seems slightly higher than LPG). With respect to transit direction, the performance is different depending on the lock: transport times are higher from south to north (from the Pacific Ocean to the PC) at Cocolí locks, while the transit times from north to south (from the Atlantic Ocean to the PC) seem higher at the Agua Clara locks. It seems that the longer trajectories in terms of time correspond to transits from the ocean to the PC, the Atlantic

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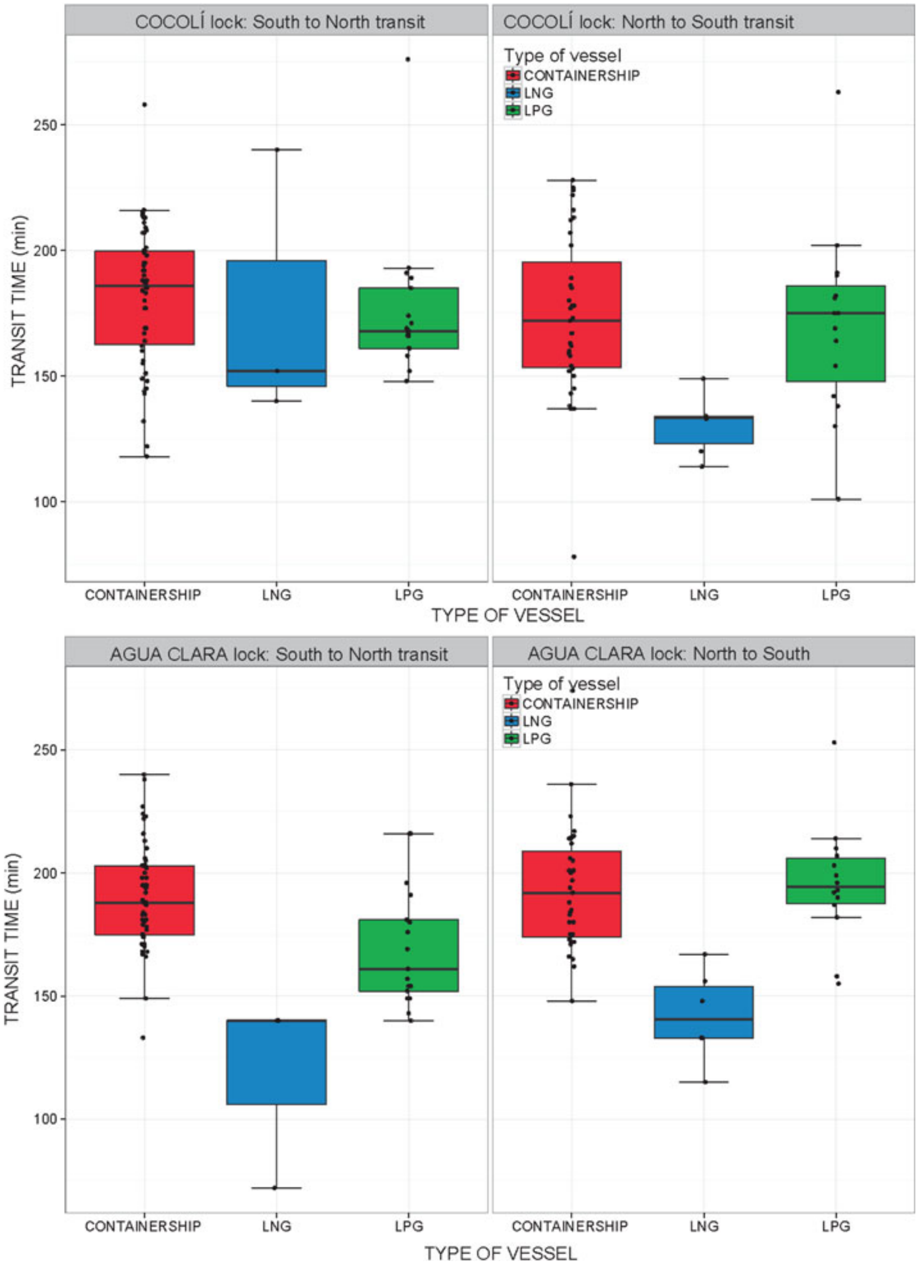

Figure 2. Boxplots corresponding to transit time depending on the values of vessel type grouped by the transit direction within lock factor (Cocolí and Agua Clara locks) are shown.

in the case of Cocolí locks and the Pacific with respect to Agua Clara locks. Moreover, in addition to Figure 2, taking into account that the mean transit times of Cocolí and Agua Clara locks are, respectively, 174.9 and 184.9 min, with similar dispersion (standard deviation of 31.59 and 28.04, respectively), it can be argued that there are different transit times

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Table 5. ANOVA table of transit time depending on the direction of transit, the lock, the type of vessel and the interaction between direction and lock.

	Sum of squares	Degrees of freedom	F	p-value (Pr(>F))	Signification at 95%
Direction	10	1	0·0134	0·9078	
Lock	6423	1	84·933	0·0038	Significant
Type of vessel	32763	2	216·63	2.08e-06	Significant
Interaction between Direction and Lock	4694	1	62·076	0·0134	Significant
Residuals	190567	252			

for each set of locks and the transit times at Cocolí are lower than at Agua Clara. These are the former statistical descriptive measurements performed in the two new sets of locks and provide an intuitive characterisation of the operational differences between the two locks, the impact of the type of vessel and the influence of the running direction.

To test if these differences in time response are statistically significant, an ANOVA analysis of three factors (transit direction, lock and type of vessel) and one interaction (between direction and lock) has been performed. This interaction has included taking into account the information shown in Figure 2. In fact, the effect of transit direction on the time is the varies depending on the lock; thus a significant interaction effect over time is expected. Table 5 shows the ANOVA table with the sum of squares and degrees of freedom to calculate the F value corresponding to each factor. The hypothesis test based on F distribution is implemented and, as a result, the effects of the lock, type of vessel and interaction of direction with lock on the transit time response are all statistically significant at a 95% confidence level (p-values $< 0{\cdot}05$). Thus, the differences in time transit shown in Figure 2 are statistically significant, and, accordingly, the developing of a regression model to estimate the time transport along the locks should include the study of these factors (when a regression model is being developed to estimate the transport time along the locks, a study of these factors must also be included).

Figure 3(a) presents the contributions of each factor in terms of % of the overall determination coefficient (R^2), in the framework of the linear model of type versus type, direction and lock factors (with interaction between lock and direction). The relative importance of each variable has been calculated using the lmg metric, the R2 contribution averaged over orderings among regressors (Chevan and Sutherland, 1991). The lmg metric decomposes the overall determination coefficient into non-negative contributions that automatically sum to the total R^2. The combination of the three factors and interaction explain the close to 19% of overall time transit variability, vessel type is revealed as the most explicative factor. If the pilot factor (person who guides the manoeuvres in each transit) is included in the linear model, the overall explained variability increases up to 44·6% (Figure 3(b)). The pilot is therefore the factor with the greatest influence over transit time, followed by type of vessel, lock and the interaction of direction with lock. In conclusion, to create a reliable model to estimate the transit time along the two sets of locks, it is necessary to take the pilot factor into account. Figure 4 shows how mean transit times and standard errors vary depending on the pilot.

Moreover, there are other factors and covariates that could affect the transit time to a certain extent. These are, on the one hand, the pilot experience (in terms of number of transits

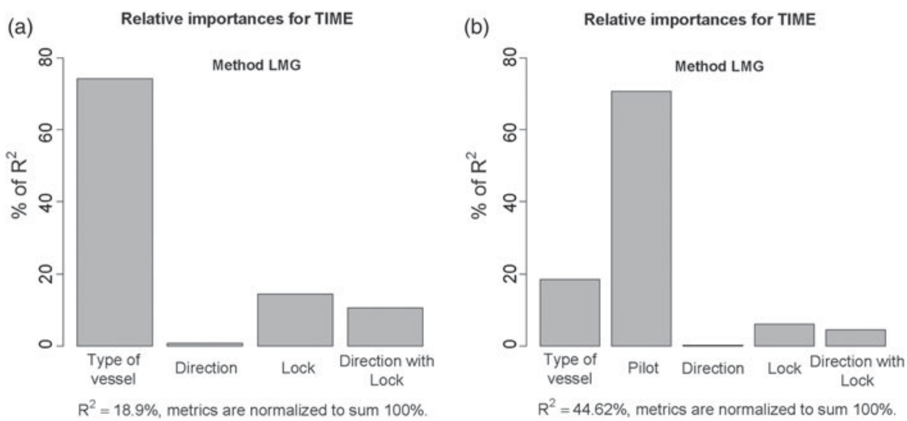

Figure 3. Contribution of each factor to the time transit explained variance in terms of determination coefficient percent. Panel (a) the contribution of vessel type, direction, lock and interaction between direction and lock is estimated. Panel (b) the factor corresponding to the pilot who performs the manoeuvres is included in addition to the above mentioned factors.

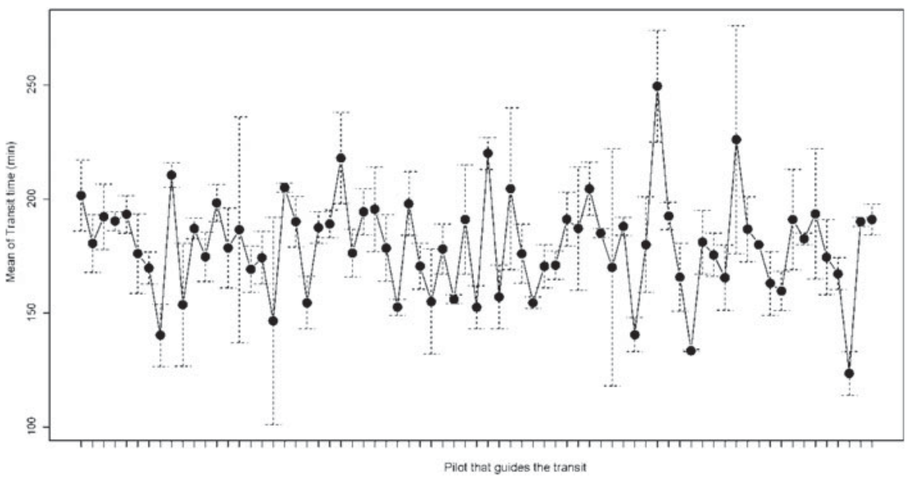

Figure 4. Mean transit times with standard error bars for each pilot.

for each specific lock) and the variables related to ship dimensions (beam and draft). With respect to dimensional variables, Figure 5 shows the dependence structure between transit time, length and draft. The density estimates are provided along the diagonal, while out of the diagonal are the scatterplots of each pair of variables, with the regression lines corresponding to each lock. It is important to note that there are very slightly linear relationships between time and dimensional variables. In fact, only in the case of Cocolí lock is there a small linear dependence between time and beam: with a higher beam, a higher time is expected. Only in the case of Agua Clara lock could the relationship between time and draft be linear to some extent: at a deeper draft, a higher time is expected. Thus, the effect of beam and draft are only considered just in those locks where a linear relationship is expected. These slight, although interesting, dependence relationships are due to

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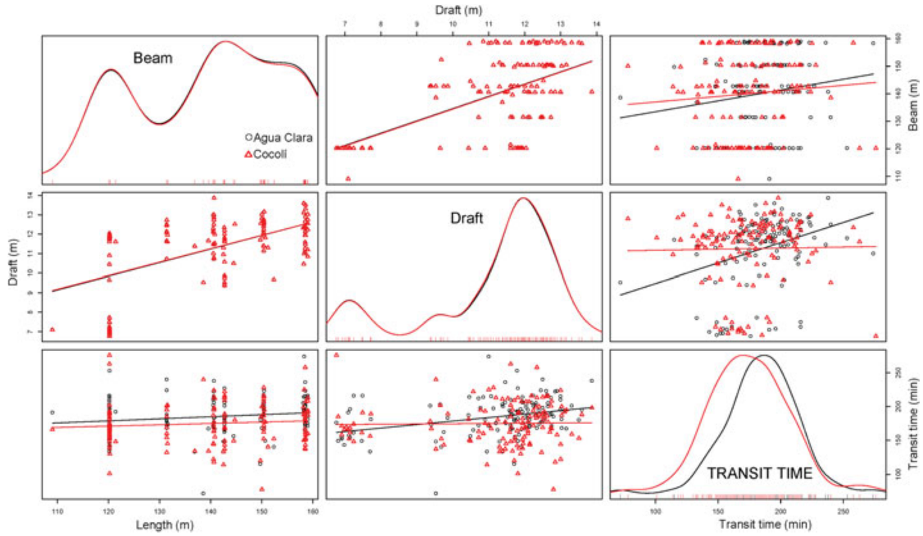

Figure 5. Scatterplot matrix with linear regression trends for each set of locks. The structure of dependence structure for vessel dimensional variables and transit time is shown. In addition, nonparametric density estimates are plotted.

the existence of other sources of variation with a greater influence, such as the above-mentioned factors. It is also stressed that, as mentioned above, transit time in Agua Clara locks is slightly higher than it is in Cocolí (Figure 5), and the transit times for each set of locks seems symmetrical and Gaussian (p-values of Shapiro test of normality > 0.05). This is important because the Gaussian hypothesis ensures that linear regression models and Shewhart control charts are applied in a reliable way. The next subsection analyses pilot experience and its relationship with transit time during the pilot learning process.

4.2. *Statistical quality control to identify pilot learning patterns.* Another important and influential variable is pilot experience along the expanded canal. The entire PC team of pilots has grown steadily in number since the first transit on 26 June (Acosta, 2016). The learning curve of the pilots is based on the number of transits along the expanded canal carried out by each. With tug operations along the locks, on the other hand, the skippers, line handlers and lock operators must have appropriate training.

Figure 6 shows the evolution of transit time with respect to the number of transits that each pilot has performed. Median transit times seem to be lower when the pilot performs the transit twice and there seems to be a slight learning effect over passage times. Therefore, this variable should be considered to obtain a model that estimates transit time.

To detect these possible pilot learning patterns properly, statistical quality tools specifically designed for this task are applied. This is possible when Shewhart control charts (Montgomery, 2007) are implemented. Specifically, transit time along locks is defined as the Critical To Quality (CTQ) characteristic in the process consisting of vessel passage through locks. The control chart tool for individual observations is then employed to estimate the natural control limits of transit time for each lock using the first 26 transits (calibration sample). In the next step, the remaining observed transit times (which are part of the monitoring sample and play no part in the control limits calculations) are plotted to detect any possible change in the process. This study has shown that transit along the new

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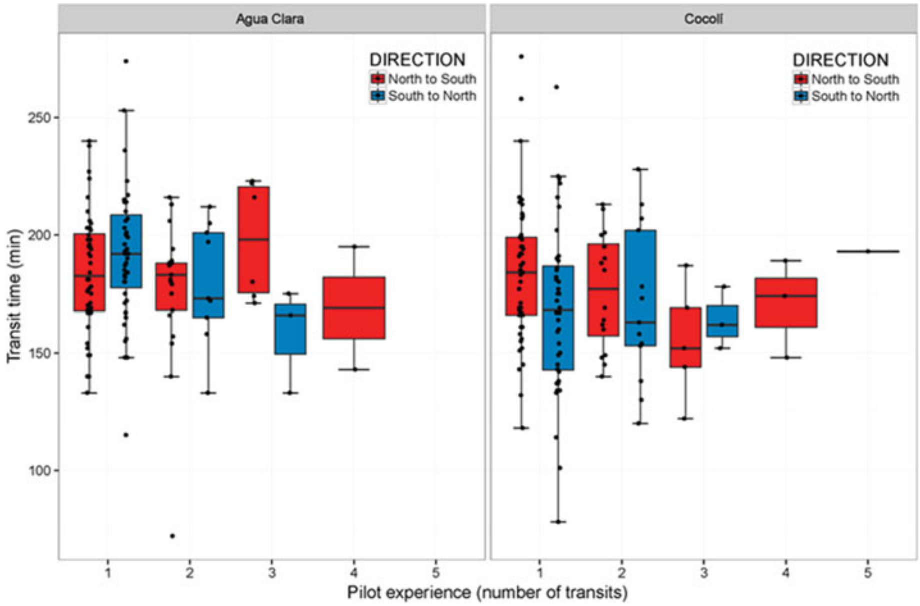

Figure 6. Boxplots corresponding to transit time depending on the values of pilot experience, grouped by the transit direction within lock factor (Cocolí and Agua Clara locks) are shown. Original observations are plotted in black.

locks is a process under control, well defined by the PCA and without assignable causes of variation, as the analysis of CTQ process variable (transit time) shows.

Figure 7 shows the Shewhart control charts for transit times corresponding to each lock, in each direction. The middle line accounts for the mean time and the dotted lateral lines at each side of the midline are the control limits for time, developed at a distance of three times the time standard deviation from the midline. The distance between lower and upper control limits is the confidence interval at a 99·73% confidence level under Gaussian assumption.

All the plot points represent the transit time observations in chronological order. Points in red account for transit time observations out of control limits and can suggest that the process is out of control due to assignable causes rather than randomness. Points in orange are named runs and indicate trends and patterns apart from randomness. They account for the existence of more than six time observations on one side of the midline (mean of time) separating the graph into two halves. In addition, learning patters are currently characterised by a gradual level change (linear trend) in the control charts (Montgomery, 2007). In Figures 7(a) and 7(b), there are no learning patterns; thus, there is no observable learning effect when the Cocolí locks are transited.

Nevertheless, there is a freak pattern in Figure 7(b) corresponding to an extremely short time due to the activity of an experienced operator. Figure 7(c) also shows a freak pattern that can be explained by an anomalously short transit time due to the work of the same pilot who, in addition, has operated an LNG vessel. As shown, this type of vessel requires shorter manoeuvring times because its overall dimensions and draft are smaller. Moreover, in Figure 7(c), a learning pattern can be observed: the transit times evolve from longer to shorter times up to a saturation region just before the end of the series. As can be seen in Figure 7(d), the variability is being reduced although the mean transit time value remains

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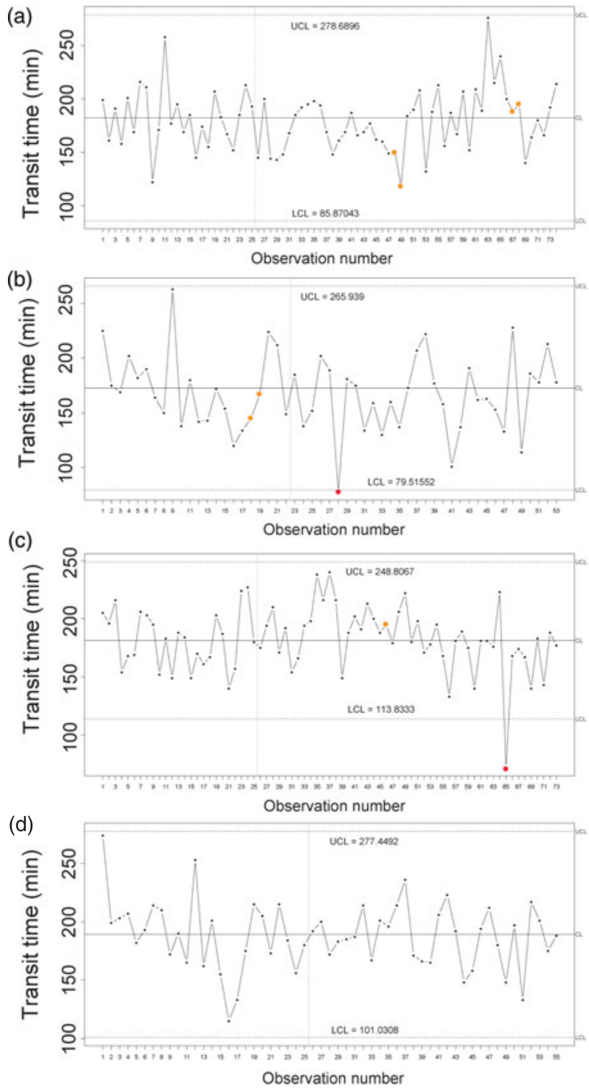

Figure 7. Control charts for transit time of the Cocolí locks transited from south to north (a) and from north to south (b), and for the Agua Clara locks transited from south to north (c) and from north to south (d).

the same. In conclusion, a slight learning pattern may happen when pilots work in Agua Clara locks and the running direction is from south to north (entering the ocean).

If the number of operations that each operator has performed (considering the running direction within each lock separately) is defined as a quantitative variable that accounts for pilot experience, linear regression modelling can also be applied to identify pilot learning patters. Figure 8 displays a very slight, although statistically significant, inverse linear relationship between transit times and pilot experience when Agua Clara lock is transited from north to south. The transit time tends to be lower when the experience or number of operations increases; therefore, a learning effect in the transit of Agua Clara lock is

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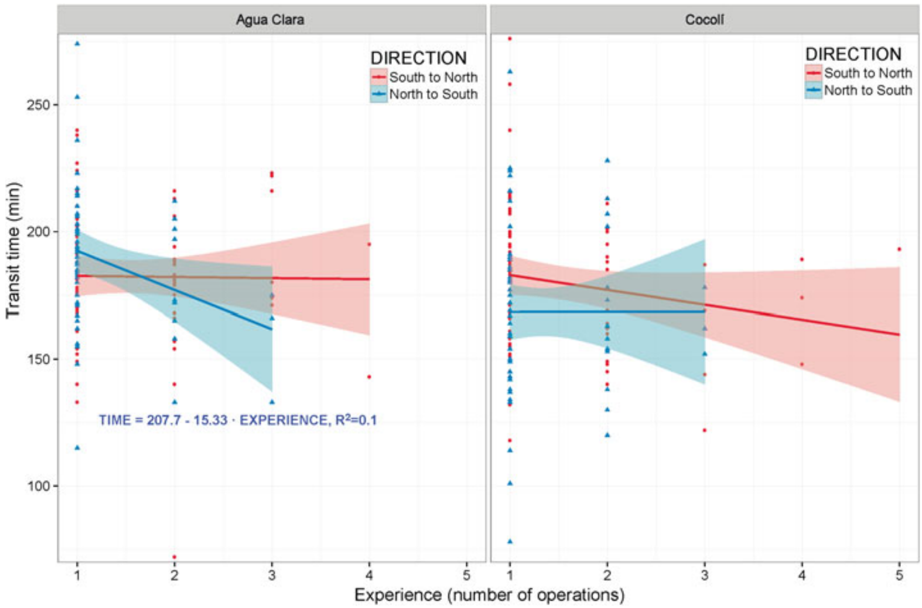

Figure 8. Linear regression models, with confidence intervals at a 95% confidence level, to model the relationship between transit times and pilot experience for each direction within each lock.

also detected. A smaller learning effect is detected in the case of Cocolí locks transited from south to north (entering from the ocean). In any case, these results must be accepted with caution considering that more experienced pilots could take greater care and longer time in berthing than less experienced pilots do. Moreover, pilots have different cumulative experience along the older locks of the canal; this factor has not been studied in the statistical analysis. These may be some of the reasons why the linear relationships between transit time and number of operations in new locks are as weak as those shown in Figure 8.

4.3. *Multivariate regression modelling to define influencing factors on transit time.* Sections 4.1 and 4.2 have shown that vessel movement (in terms of transit time) is conditioned by its main dimensions, vessel type, pilot, pilot experience, transited lock and transit direction. Of the length, beam and draft, the third is the most determinant value, especially when this figure approximates the maximum for the canal (Chen, 2010). Although the main dimensions are the same, distinct displacement values, underwater body and upperworks shapes and propulsion power are obtained for the various types of vessel. All of these aspects condition how the vessel moves along the locks and waterways.

Once the influencing variables are identified, the next step is to find an expression to estimate transit time as a function of the above-mentioned factors and covariates. Considering that vessel transit time depends on many different variables, the time modelling problem should be tackled from a statistical multivariate approach. Considering the information shown in Figures 5 and 8, multivariate linear regression models are proposed. As displayed in Figure 3, the transit time depends on the type of vessel, lock factor, transit direction and on the interaction between lock and direction. The resulting model is defined

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by the linear Equation (1) with $R^2 = 0.1$, where all the factors are statistically significant.

$$Time = 185{\cdot}9 - 44{\cdot}97Type[LNG] - 7{\cdot}3Type[LPG] - 2{\cdot}6Lock[Cocoli] \\ + 9{\cdot}1Direction[South] - 17{\cdot}2Direction[South] : Lock[Cocoli] \quad (1)$$

Thus, the effects on transit time of an LPG type ship and Cocolí locks are negative (decreasing the response variable). In contrast, an LNG type vessel and the interaction of a southerly direction and Cocolí locks present a positive effect on the response (increasing the transit time). In any case, pilot factor must be included due to its strong influence on lock passage time response.

Different models have been proposed for each group of locks, Cocolí and Agua Clara, respectively, taking into account that it has been shown that transit times are significantly different depending on the lock factor and the interaction of transit direction and lock.

Considering the passage times along the Cocolí locks, in Figure 9, a summary of the multivariate linear regression model for transit time in Cocolí lock is presented,

$$Time = f\,(pilot, typeof\ vessel, experience, direction) \quad (2)$$

The independent variables have been selected using a step backward/forward automatic procedure based on the Akaike information criteria (Venables and Ripley, 2002). The determination coefficient is about 61%, and the most influential variable is the pilot, whose contribution to R^2 is more than the 80%, followed by the type of vessel, direction and pilot experience. The linear effects over the time of each factor are presented in Figure 9(b). As mentioned in Section 4.1, the transits with a north to south direction are conducted in shorter times, LNG ships also perform the transit in shorter time intervals and increased experience (number of manoeuvres) produces a significant decrease in passage time. Methodological variables and other features that have not been included in this study could model the remaining time variation that the present model does not explain.

With respect to Agua Clara lock, two multivariate linear regression models were created. In Figure 10, the multivariate linear regression model for transit time in Agua Clara lock, Equation (3), is summarised.

$$Time = f\,(pilot, type\ of\ vessel, draft, direction) \quad (3)$$

As in the case of Cocolí locks, the independent variables have been selected by a stepwise method based on minimising Akaike information criteria (Venables and Ripley, 2002), with the residuals meeting the entire linear model hypothesis of normality, independence and homoscedasticity. In this case, the determination coefficient is $R^2 = 78{\cdot}35\%$; thus, the model explains 78·35% of transit time variability. The most influential variable is also the pilot, whose contribution to R^2 is almost 70%, followed by the type of vessel, draft and direction. Transit in a south to north direction is performed in a shorter period, the LNG vessels also pass through the Agua Clara locks in a shorter duration and an increase in draft raises transit time in a linear way. It is important to note that all the independent variables are statistically significant. Another interesting point is that the draft variable's effect over the response is significant only in the Agua Clara locks (for more intuitive information of transit through Cocolí and Agua Clara locks see Figure 6). To stress the importance of the human factor in Cocolí and Agua Clara manoeuvres, a multivariate linear model has been proposed discarding the pilot factor. A stepwise process of variable selection

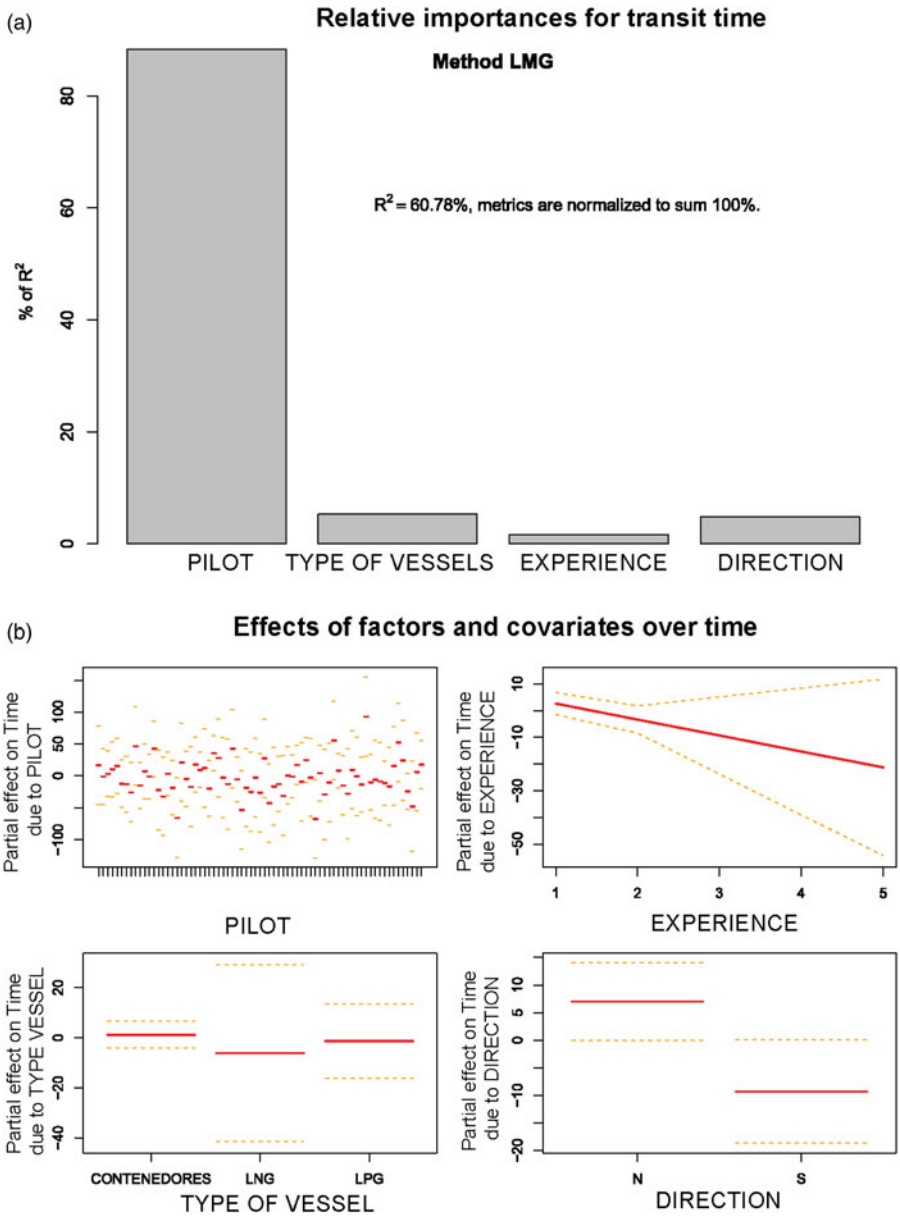

Figure 9. Characteristics of the linear regression model relating the transit time to the pilot, type of vessel, pilot experience and transit direction for the Cocolí locks. Section (a): estimate of the relative influence (in % of R2) for each regressor variable applying the LMG metric. Section (b): Partially linear effects of the pilot, type of vessel, pilot experience and direction.

based on Akaike Information Criterion (AIC) minimisation is used again so that the model Equation (4) with $R^2 = 0{\cdot}4$, is obtained, where date is the number of days passed since the experiment has begun, and bow propeller is a factor that indicates if this device is used or

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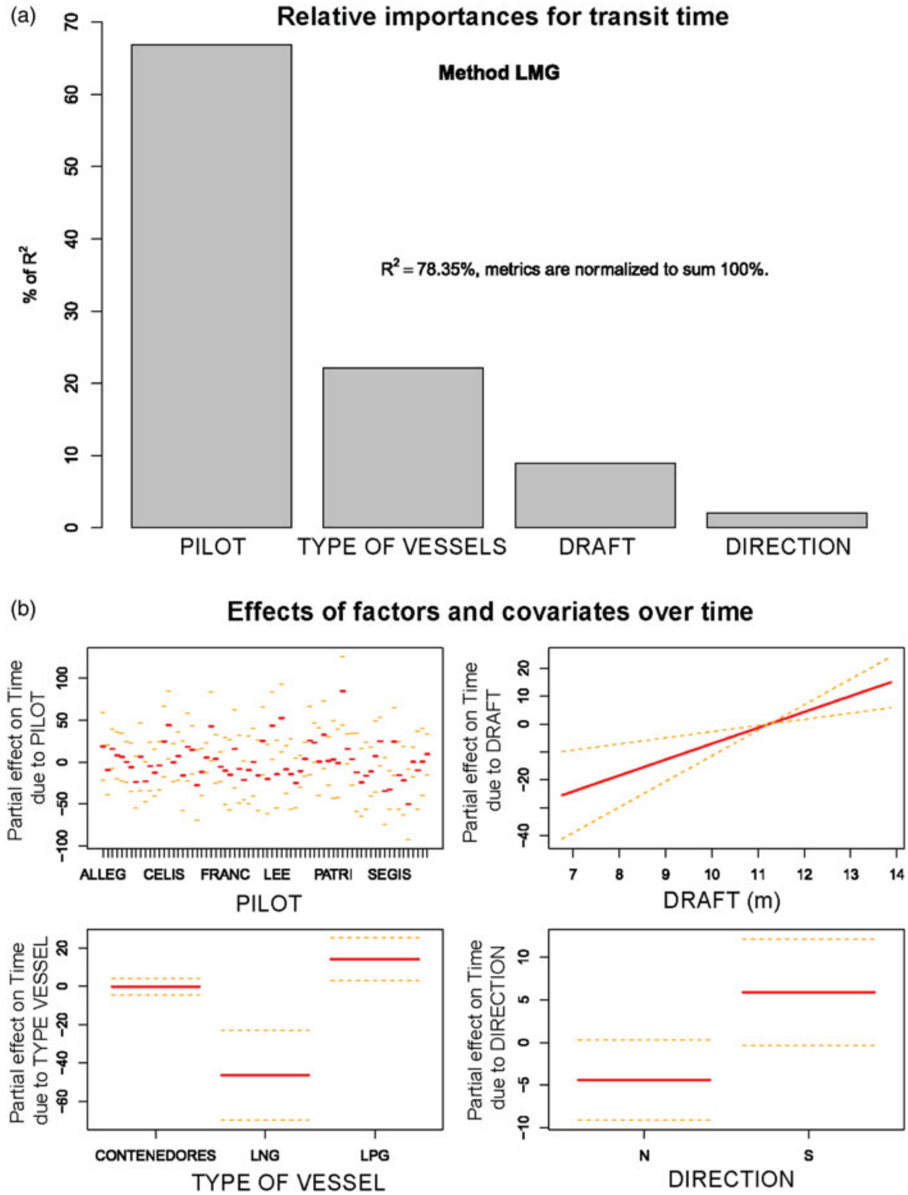

Figure 10. Characteristics of the linear regression model relating the transit time to the pilot, type of vessel, pilot experience and transit direction for the Agua Clara locks. Section (a): estimate of the relative influence (in % of R2) for each regressor variable applying the LMG metric. Section (b): Partially linear effects of the pilot, type of vessel, pilot experience and direction.

not in the manoeuvres.

$$\begin{aligned} Time = 276{\cdot}6 - 0{\cdot}2458 Date + 4{\cdot}706 Draft - 52{\cdot}26 Type[LNG] - 2{\cdot}91 Type[LPG] \\ + 9{\cdot}526 Direction[South] - 17{\cdot}2 Bow\ propeller[Yes] \end{aligned} \tag{4}$$

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Figure 11. Panels (a) and (b) Neopanamax container ships transiting through the Cocolí Lock. Panel (c) The *Ever Lenient* container ship transiting the Agua Clara lock, 20 August 2016. Panels (d), (e) and (f) The *Sunstar* LPG ship transiting through the new locks and Gatún lake. Panel (g) The *Aegean Unity*, first Suez-Max type oil tanker, 21 August 2016. Panel (h) The *Galea*, the first Kvaerner Moss type LNG carrier, transiting the canal 26 August 2016. Source: PCA.

The model is far less explicative than one in which the pilot factor is included. Nevertheless, it shows that transit time also depends on other, new variables related to manoeuvres: for example, the use of bow propeller is related to shorter transit times. The acquisition of experience also comes into play. As time passes, transit times grow shorter. Although the dependence on time and these variables is weaker, and thus masked by the pilot factor, all these independent features are significant at a 90% confidence level.

Soon transit times will almost certainly be affected by new variables yet to be analysed. Among the variables that will need to be considered in subsequent studies are:

- The impact of seasonality. This is particularly the case with the dry season, when the crosswinds across the locks are stronger. Moreover, in the dry season, water recycling basins are used more. These factors increase lockage times.
- The impact of a higher number transits per day, which will continue to be a trend in the newly expanded canal.

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– Standardisation of manoeuvres. Currently the Panama Canal Authority has not imposed a standard operational system for manoeuvring. However, over time, a number of operational modes along the locks that are now being used (see Table 3 - operational modes) will become standard practice. This trend will also affect lockage times.
– Enhanced learning curves. Over time, as the personnel are better trained and more experienced, they will undoubtedly improve their lockage times.

5. CONCLUSIONS. Expanding the Panama Canal will undoubtedly mean that a new kind of vessel comes into existence; a similar phenomenon occurred with the pre-existing canal. In their dimensions, these Neopanamax ships will be adapted to how the locks might operate.

The manner in which vessels are manoeuvred through the locks also varies. Two tug boats - one at the prow and another at the stern - position the ships within the locks. While the ship is inside the chamber, which is being filled and drained, it is immobilised with the help of the mooring system and the linemen on board and along the Canal. Over the first months that the operating system has been working, it has become more efficient. This trend can be seen with the slight decrease in transit times detected in the statistical analysis.

In terms of lock transit times, a comprehensive statistical analysis has been carried out to identify the influencing factors and covariates. In this way, a model is obtained to estimate and characterise the transit time along the new Cocolí and Agua Clara locks. Exploratory analysis and ANOVA have shown that the factors with the greatest influence on the transit time are the pilot who guides the operation, vessel type, the lock transited and the interaction between direction and lock. LNG vessels are faster than container ships and liquid petroleum gas carriers in transiting the locks. Another point of interest is that travelling along channels that start from either the Atlantic or Pacific is more time-consuming, due to the special characteristics of the manoeuvres.

Moreover, transit time is somewhat dependent on pilot experience in the newly expanded canal. In fact, significant pilot learning patterns are identified in Agua Clara locks when regression modelling and Shewhart control charts are used for individual measurement. When the number of piloting manoeuvres increases, transit time goes down. The influence is not as strong as expected because the locks have only recently been opened. In terms of the dimensional covariates influencing time, the linear effect of the draft variable on the response is significant. However, this is only the case in the Agua Clara locks where a significant linear relationship is detected: when the draft increases, transit time also does at a constant rate.

These dependence relationships have been modelled by multivariate linear regression. As a result, two different models have been obtained, one for each group of locks. The influence of lock over transit time is taken into account. For example, when it comes to mean values, the transits along Cocolí locks tend to be shorter than those in Agua Clara. The most important factor on transit times is the pilot, highlighting how important the human factor is. If this factor is not considered, the influence of other variables relating to type of manoeuvres is identified. This can be seen when bow propellers are used in Agua Clara, and a significant decreasing of transit time is observed. Finally, it is important to note that the transit process along the new locks is under control. In other words, it is a stable process, without sources of variation apart from those common to the process, even though there are many possible sources of variation in such a complex process. One of the main concerns is the professional levels of Panama Canal personnel.

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