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SYNERGISTIC APPROACH TO PORT DEVELOPMENT

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Abstract: The research based on the analysis of existing theory of port development prediction and control reveals the contrariety between existing models and the requirements of practice. Historically formed toolkit briefed in previous publications of the authors and summarised in this article does not answer to the strategic question of the decision-makers about the development program of a given port. Existing models explain in detail why the port was developed in a particular way without elaborations of the exact directions for future development. Due to the nature of the studied subject it is impossible to create a single model of the process of port development using the traditional methodological principles, which fact is postulated in the article. Since the modern port is a complex, stepwise, multi-level dynamic system, it cannot be adequately mapped using traditional linear system, which is a methodological simplification of reality. As a result, the port models constructed within the linear paradigm suffer significant loss of properties, which from the outset limits the scope of their applicability. To study the strategic characteristics of port development, especially included in the associated spatial-economic clusters, it is convenient to make use of well-established research in other fields of knowledge. The principal task of the authors was not the transfer of the general provisions of this theory and the creation of a methodological concept which is already used in the transport business, but elaborating specific models of development, focusing on the study of the qualitative and quantitative characteristics of the studied objects. The paper represents the results of modeling the interaction and evolution of port populations serving the hinterland. The results confirmed the theoretical assumptions and the possibility of achieving stated goals.

Keywords: seaport, development models, synergy approach, modelling.

1. ANALYSIS OF EXISTING MODELS OF PORT DEVELOPMENT

Fundamental changes in the world economy and transport infrastructure have occurred over the past decade, and seaports have been as affected by this as by any other aspect. Today, these key infrastructure elements are in need of solutions that take into account the challenges of the modern world: competition, environmental pressures, lack of space, lack of capacity, and the requirements of logistics and supply chain management. Success or failure in dealing with these issues depends on how well the port sets its development goals as well as how to achieve these goals. The initial capital required for the construction of the port infrastructure, and the fact that once something has been done it is very difficult to reverse, leads to high rates of error in determining the course of development.

The theory and practice of forecasting and managing the development of ports has been actively studied since the middle of the last century. The result has been the creation of a number of models describing the steps of development that are influenced by a number of port-specific forces. According to the researchers, these steps determine the development of ports. The English scientist James Bird proposed the first model of a port in 1963, which described how port infrastructure develops, both spatially and over time [Bird 1980]. In his concept, Bird describes the six stages of development of a port:

- *Setting of the port*: this step includes the initial forming of a port, marked by small and shallow piers, adjacent to the city centre;
- *Marginal quay extension*: achieving the possible expansion of the boundaries of the port in the city centre, without building new cargo berths;
- *Quay elaboration*: the port has reached a stage where the technical possibilities for processing vessels in the initial berths have reached a maximum. This is associated with the development of cargo handling equipment and the size of the vessels;
- *Dock elaboration*: this stage of expansion of the port, and the creation of new, deeper and extended berths capable of taking larger ships and in greater numbers, is in most cases associated with a move along the shore towards the mouth of the river.
- *Simple lineal quayage*: this stage is typified by the modernisation of cargo handling equipment, in order to speed up the processing of large vessels and tonnage;
- *Specialised quayage*: this stage is typified by the orientation of the quays and port handling equipment towards the processing of specific types of vessel and cargo.

The author notes two main strategies of port development:

- *spatial development*, which can be recognised as a movement away from the city centre, by creating new deep-water multi-purpose berths in available space. At the same time there is a gradual change in the usage of the original port areas of the city. These areas are usually located close to the city centre, and are often converted into parks, housing, and commercial developments;
- *specialised handling equipment*, or the creation of cargo handling facilities or ports, which enable faster processing of specialised ships, and reduce cargo handling costs.

Bird noted that port development is gradual. Different parts of the port may be at different levels of development at any one time. This means that sub-optimal equipment may be in use in some parts of the port, while others are using units that are more modern.

Although initially Bird's model was shown to be effective, it has displayed a lack of flexibility. Attempts have been made to resolve this, by introducing several phases: *closure, expansion, addition, consolidation*, and *conversion*. On the one hand these 'fixes' allow us to better explain the process of development of a specific port, but on the other hand can lead to the loss of universality of the model. Some authors believe that the six steps can be grouped into three main phases: setting*, expansion* and *specialisation*. The first such proposal was made by the J.P. Rodrigue and T. Notteboom (Fig. 1) [Notteboom and Rodrigue 2005].

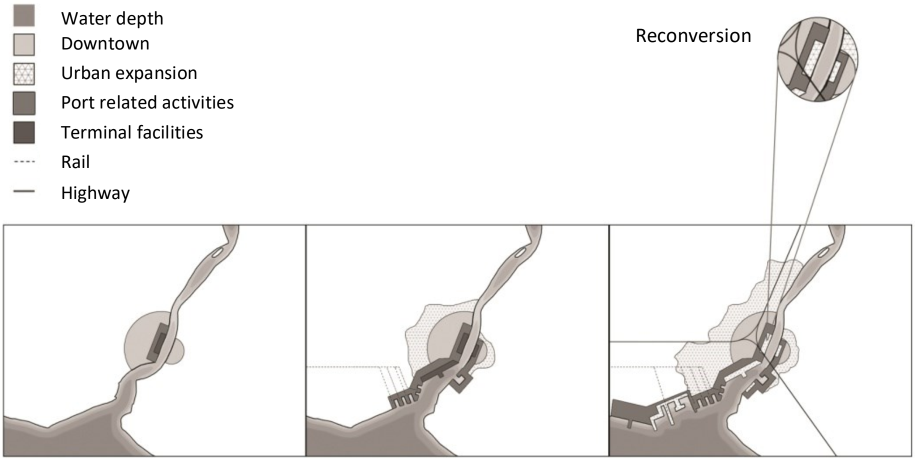


Fig. 1. The stages of port development according J-P. Rodrigue, T. Notteboom [2005]

At the same time, Bird emphasised that he developed his model based on the stages of development of certain ports, and that it was not designed to meet the criteria of all ports. He acknowledged that a model of port development could be based on various factors. Although his model is called 'Anyport', it is based on the development of port facilities to meet the growing needs of the fleet, and does not take into account factors such as the relationship of the port with the city, the availability of hinterland and its development, and the specialisation of ports [Kuznetsov and Galin 2015].

The United Nations Conference on Trade and Development (UNCTAD) in 1985 presented its own concept of port development, summarising the results obtained by Bird and his fellows, and focusing on the cargo-handling aspects of port operations [UNCTAD 1985].

This concept was based on the fact that the driving force behind the development of ports is the increasing volume of cargo flows and changes in the structure (Fig. 2).

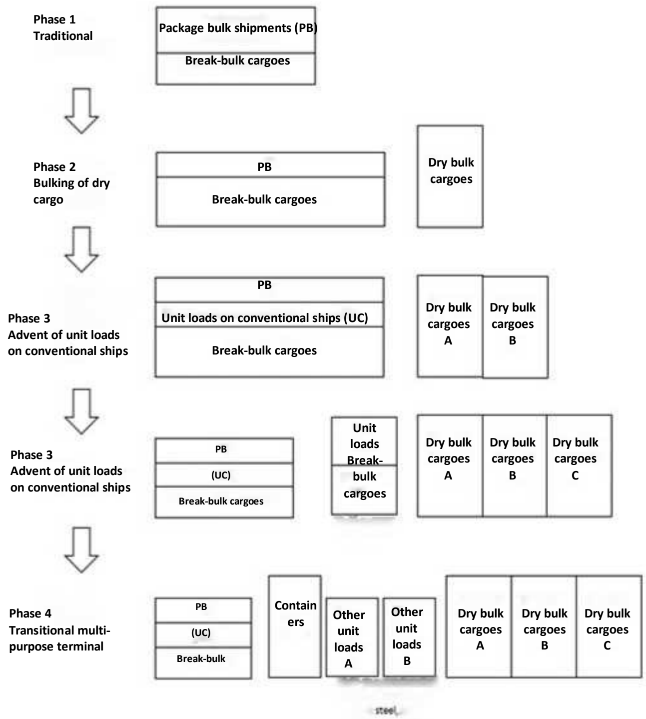


Fig. 2. Steps for port development in accordance with UNCTAD [1985]

In accordance with this concept, a suggestion was made to divide the development of ports into five stages.

Traditional. At this stage of development, the port is just a group of general-purpose berths that are capable of handling general cargo --for example piece and bulk cargoes in packaged form, such as wheat in bags, oil drums, and fertilisers in bags, or cargo with packing in the hold.

Bulking of dry cargo. Upon reaching certain cargo size levels, it becomes economically feasible to transport a bulk cargo load on specialised ships known as bulkers. Some of the total volume of the cargo is defined as a special new type of cargo flow – bulk cargo, for which the port has to provide a separate berth with specialised lifting and handling equipment. Therefore, the appearance of bulk cargo terminals is a natural requirement. At the same time, equipment for handling general cargo is modernised and mooring lines are expanded as a result of the constant growth in traffic and of the size of vessels.

Advent of unit loads on conventional ships. This stage is characterised by two major trends. The first of these is the appearance of a means of integrating packaged unit loads: pallets, big bags, boxes, crates, containers, packages (metal rods, pipes and so on.). Firstly, these make up a small proportion of cargo traffic. Handling this type of cargo takes place on general cargo and shipping quays, using conventional vessels. The second trend is a steady decrease in the volume of general cargo due to its reallocation as bulk cargo. At the same time, the volume of bulk cargo is considered to have reached a significant level when different terminals are required for different types of bulk cargo.

Transitional multi-purpose terminals. The increased usage of consolidated cargo units (CCU) and the emergence of specialised vessels for their transportation (lumber carriers, car carriers, ro-ro ships, container ships and other cellular container types) all require special handling equipment. At the same time, the cargo flow of each type of CCU is small, and the prioritisation of CCU cargo traffic in the future is unclear, due to which the need arises for a flexible multi-purpose terminal, which replaces the older general cargo berths.

This type of terminal can easily be converted into a specialised terminal for cargo, as long as it is of a sufficiently high level to be able to cope with different types of cargo. This will be a priority in the near future. Additionally, this stage will see a continuation in the growth and diversification of the flow of dry bulk cargoes.

Specialisation. The final stage in the development of any kind of traffic is for it to reach such a volume that it is necessary to use a specialised fleet for its sea transport and specialised terminals to handle it in the port. In this case, multi-purpose terminals can be easily converted into terminals specialised for the processing of through cargo. This can be achieved through the purchase of additional equipment and slight modifications of existing equipment. By the time the fifth stage is reached, the residual volume of general cargo is significantly less than it had been, and the processing of the main cargo types (timber, iron, steel) is grouped in the multi-purpose terminals.

This model explains the historical reasons behind the changing nature of sea traffic and port development strategies. However, it has limited applicability in the present context of prevailing factors that influence cargo traffic. The model is based on just one factor, albeit one which heavily influences the development of the port with regards to the long-term potential for economic change. The influence of other relevant factors is ignored.

The increase in commercial factors, efforts to expand the port area, and the emergence of the concept of the port as a ‘service centre’, all mean that a new understanding was required, of how to develop ports, and why this was needed. By the end of the twentieth century, UNCTAD, drawing attention to the radical changes taking place in the role of ports in the world, introduced a new stage for the model of development studies [UNCTAD 1992]. As a result, the conceptual model, which includes three generic phases, or ‘generations’ of port development was proposed, as Table 1 shows.

Table 1. Port development models by UNCTAD [1992]

Period of development	First generation	Second generation	Third generation
	Before 1960s	After 1960s	After 1980s
Main cargo	Break bulk cargo	Break bulk and dry liquid bulk cargo	Bulk and unitised containerised cargo
Attitude and strategy of port development	Conservative Changing point of transport node	Expansionist Transport, industrial and commercial centre	Commercially oriented integrated transport centre logistic platform for international trade
Scope of activities	1 – Cargo loading, discharging, storage, navigational service Quay and waterfront area	1 + 2 – Cargo transformation, ship-related industrial and commercial services Enlarged port area	1+2+ 3 – Cargo and information distribution; logistics activities Terminals and distribelt towards landside
Organisation characteristics	Independent activities within port Informal relationship between port and port users	Closer relationship between port and port users Loose relationship between activities in port Casual relationship between port and municipality	United port community Integration of port with trade and transport chain Close relationship between port and municipality Enlarged port organisation
Production characteristics	Cargo flow Simple individual service Low value added	Cargo flow Cargo transformation Combined services Improved value added	Cargo information flow Cargo information distribution Multiple-service package High value added
Decisive factors	Labour capital	Capital	Technology know-how

The principles of the division are based on a set of key factors: port development policy; strategy; scope and limits of the expansion of the port area; the degree of integration of port functions and organisational structure of the port. At the same time, the concept also discarded a number of important factors, such as the scale of the port, its geopolitical situation, and the ratio of public to private ownership. The development has been studied in a modular fashion, and the transition from one generation to another was associated with the growth of the port, and is partly determined by the motivation of decision-makers.

First generation ports in this model play the role of an interface between sea and land transportation. They were not designed for any transportation or trading activities, and therefore were far from meeting customer requirements. The same detachment and lack of interaction can be observed between the port and local authorities of the city in which the port is located. They were independent from each other, and never considered cooperating in order to promote the port on a commercial level.

Second generation ports differ already in that they offer several advanced functions, such that they can be considered to be a ‘centre of transport, industrial and commercial services’. All these new features can be described as ‘commercial activities, adding cost to the cargo handling operations’. The port becomes more open to cooperation with the transport industry and freight principals as well as to cooperation with the relevant local authorities. Second generation ports are no longer geographically isolated from the rest of the transport industry.

Third generation ports are the product of a globalised and integrated world. They are treated as dynamic components of international production and distribution systems, forcing the owners to adopt a pro-active approach. This turns ports into integrated transport centres and logistical platforms for international trade. The functions of such ports are more specialised, diverse and integrated, yet still have all the features of first- and second-generation ports. At this point, the importance of using modern port equipment and advanced information technology starts to become very clear.

Industrial services in this model are divided into two categories: vessel-oriented and cargo-oriented. In order to aid the development of the latter, industrial zones were created, the purpose of which was to attract traffic. At the same time, development began of environmental measures, which were aimed at reducing the harmful effects of port operations.

The third generation of ports dramatically increased administrative efficiency, by way of improving the processing of documentation, and with the appearance of modern information technologies. The quality of day shift planning has also improved, ensuring the best use of port infrastructure. The administrative and enhanced commercial services of third generation ports reached a new level of quality.

Third generation port operations incorporated into its capabilities both goods distribution and logistics systems. This freed the ports from their traditional functions of medium and long-term storage of goods. Containerisation has also transformed the port into a ‘checkpoint corridor’, where the goods are no longer delayed, thus reducing the chances of incurring additional costs.

The model described is a useful tool for analysis and comparison, which has made it a popular and well-recognised tool for several decades. At the same time, the simple ‘black and white’ analysis inherent in this model of development quickly made it less realistic and accurate, as non-representative events influenced the rapidly developing world port industry. Practitioners noted that the development of ports did not always follow distinct stages, and not all ports followed the same cycles for the transition to the third generation.

Moreover, some port terminals displayed a different line of development in response to specific requests. Commercial pressures and goals were the main determinant of this development along with continuous process of the introduction of new equipment and technology.

As a result, even the most advanced ports in terms of systems, equipment or terminal port projects often retained aspects of the earliest stages of development, which contributed to overall efficiency.

In addition, shipbuilding and shipping organisation have showed changes that were not predicted during the creation of the models of the 1980s. A considerable complexity of objective classification of a port of any particular generation has arisen: the procedure has always been quite subjective, and therefore carries a risk of error, since to a greater or lesser extent every port is unique.

Most of the important processes described in terms of successive generations of the UNCTAD port model were ambiguous and imprecise. Development is not fixed at any one time and does not necessarily pass through the development cycle to achieve third generation of port status. Therefore, the model selection of distinct 'port generations' may not accurately reflect the port industry on a global scale.

With careful study, it becomes clear that this model does not reflect the situation that has dominated over the past four decades. A wide range of other factors, such as port size, geographical location, work culture, and the degree of public/private involvement, have all showed significant changes. All this must be taken into account in order to better describe the current situation in the ports, which could not realistically be divided into categories of 'generations'.

Fundamental problems with the model of 'port generations' mean that models can no longer include all the changes that have occurred in the port business over four decades.

The characteristics of ports should not be categorised according to a rigid conception of discrete chronological stages. The model should reflect changes over time and at the same time should consider the importance of categories for individual aspects. In this sense, it is necessary to include a much wider range of properties and characteristics than those that were predicted in early models.

Such aspects as the culture of doing business in a given port, labour issues and social concerns, the protection of the environment, and other matters began to take on increasing importance.

All of this led to the emergence of a new port development concept model, which was given the name WORKPORT [Beresford et al. 2004]. The main features of this model are shown in Table 2.

Table 2. Schematic model of the processes in ports, according to the WORKPORT model [Beresford et al. 2004]

	1960-e	1970-e	1980-e	1990-e	2000-e
Ownerships	Infrastructure mainly public sector owned (exceptions in UK) Superstructure and cargo operations either private or public sector depending on country and/or port Increasing private sector involvement particularly in provision of superstructure and cargo operations	INCREASING PRIVATE SECTOR INVOLVEMENT	Privatisation of nationalized ports in UK Some concentration of ownership of UK ports Increasing commercialisation of port authorities Ports becoming more customer-orientated Further privatisation in UK ports	Greater concentration of container terminal ownership through partial acquisition by multinational terminal companies	
Cargo forms	General cargo: -Substitution of unitised methods for break bulk methods begins - General cargo splits into containerised ro/ro, palletised, LASH, neo-bulk, break bulk Dry bulk: Little change in form Liquid bulk: Little change in form	SUBSTITUTION OF UNITISED FOR BREAK BULK	Increasing ship size		Unitisation of general cargo almost complete
Cargo-bandling processes	General cargo	INCREASING AUTOMATION & MECHANISATION Becoming increasingly mechanised and automated with unitisation		Full automation of quay and stack operations at a few container terminals (robotics)	
	Dry bulk — Highly mechanised	Specialised terminals	полная автоматизация		
	Liquid bulk — Highly mechanised and automated	Specialised Terminals	увеличение автоматизации		

	PROLIFERATION OF METHODS				
Cargo support processes and information provision	Communication, documentation and information exchange Manual/paperbased recording	Mail, telephone, cable	Mail, telephone, radio, fax, telex, EDI	Mail, telephone, fax, radio, telex, EDI, internet, intranet	Standardisation of information
	DECREASING NUMBERS OF WORKERS				
Working culture ***-Labour force*** ***-Work organisation*** ***-Working environment*** ***-Employment conditions*** ***-Labour relations***	Break bulk cargo operations labour intensive, although other cargo operations capital intensive Much manual work. Dock labour highly unionised Hierarchical organisational structure	Unitisation of general cargo operations leads to mechanised tasks being substituted for manual ones Greater specialisation of workforce Work force decreasing in number (despite increasing cargo volumes)	Multi-skilling of core workforce Flatter organisational structure, Increasing requirement for IT skill 24 hr working becoming increasingly common Substitution of contract workers (agency workers) for labour pool workers begins at some ports (ending of NDLS in UK in 1989)	Greater emphasis on quality aspect of services provided	Labour pools phased out
	INCREASING DIVERSITY OF PORT RELATED ACTIVITIES				
Port function/ Port development processes	Interchange point between maritime and inland transport Cargo focused, but with some related ancillary activities within/outside port area, e.g. oil refining Informal relationships between ports and port users	Increasing industrialisation (e.g. MIDAS) Enlargement of port area Closer relationships between ports and port users	Diversification of port-based companies (e.g. into logistics and value added services) Emergence of freeports and distribution centres United port communities	Globalisation of port communities	Globalisation of port communities
	DECREASING ACCIDENT RATES AND ABSENTEEISM				
Health and safety aspects of the working environment	Port work dangerous because of high proportion of manual tasks and inadequate regulation and insufficient training	Decreasing accident rate, and reduced absenteeism due to health problems Fewer accidents and physical health problems due to reduction in manual tasks (but when accidents occur, more likely to be catastrophic)	Better ergonomically designed cargo equipment	Improved training in safety awareness Formal health and safety policy EU Working Time Directive Tightening environmental control in the workplace	
	INCREASING ENVIRONMENTAL AWARENESS				
Environment	Generally low level of awareness	Reactive response to incidents	EU environmental assessment Specific legislation Increasing awareness Ad hoc local initiatives	Increasingly proactive environmental management systems EU Habitats Directive ESPO ECO-Code info	Quality-assured EMS Compliance plus environmental issues integrated into business plan
Decisive factors	Labour intensive	Capital intensive-introduction of new technologies	Further advances in technology and knowledge base	Information and communication technology	Integration of the interests of the whole port community

In this table, arrows show the main trends observed in the development of ports, which are the key to finding ways to improve efficiency and growth opportunities for both the port authorities and the companies operating in the port. Eight factors that characterise the development of the port have been chosen, plus a factor that characterises the main difference between each development period. The eight factors are: ownership; form of cargo; cargo handling processes; cargo support processes and information technology; work culture; port functions and port development process; health& safety and, environmental protection.

In the 1960's, ports were mostly a point for load division between sea and land transport. Because of this, they were focused on cargo, but only concerning the aspect relating to the movement of goods from one mode of transport to another.

In the 1970's, port functions and processes gradually developed in conjunction with the free trade zones which were emerging around the same time and within the context of closer and more comprehensive relations that began to take shape between the ports and port users.

In the 1980s, parts of ports diversified within the developing field of logistics and began offering services that added value. The transport chain was integrated to varying degrees depending on a particular load and customer requirements.

The 1990s showed the development of the globalisation process in the port industry in the form of mergers, acquisitions and joint operations which were becoming increasingly common and complex. The authors emphasise in the model that all the changes that occurred in the development of the port functions were evolutionary rather than revolutionary, as shown in the 'port generations' model.

The WORKPORT model greatly expanded the range involved in the analysis of the factors and characteristics that were taken into consideration, adding new connections and patterns, and thereby serving as an important step in the development of theoretical concepts. At the same time, the WORKPORT model favorsmeaningful descriptions of and statements about events, making it difficult to use it as a tool for forecasting and analysis of the general type. In addition, this model does not fully reflect the role of the advanced development of logistics and the influx of new processes.

As a response to the emerging social needs in the area of the port and the transport and logistics business in the late twentieth century, Rodrigue and Notteboom proposed several models that develop these ideas. They combined different approaches, taking into account aspects of urban development. The authors added the factor of 'port regionalisation' to Bird's models. This allowed them to explain the reasons for the emergence and development of transhipment ports, the formation of logistics poles, and other aspects of the integration of ports in the hinterland (Fig. 3).

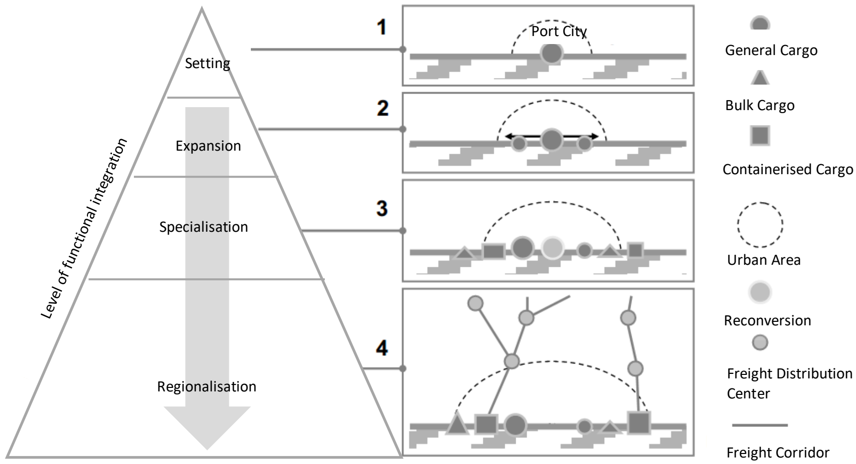


Fig. 3. Port Development Model Rodrigue and Notteboom [2005]

The revised model of development of the port system was based on two main provisos. The first point combines offshore hub ports with an insular location (and continental ports with limited hinterland) into a single system of container distribution, which forms a hinterland with other continental ports, to which they are connected by feeder lines.

The second point relates to the inclusion of inland freight terminals as active centres in the formation and development of port hinterland. The port regionalisation phase is added to Bird’s model as the next stage of development, marked by a strong functional relationship (and even joint development) between ports and multimodal and rear logistics platforms. This leads to the formation of a regional network of commercial centres and to the expansion of port hinterland (Fig. 4).

The key difference in the model of port regionalisation lies in the fact that it explores the development of ports in terms of dynamics and considers hubs, rear logistics platforms and ports as a single system, forming a goods distribution network. The authors of the model indicated that during the transition to this phase, there is a gradual regionalisation and market-driven process which influences the port, and draws the attention of market participants to the integration of logistics. At the same time, the concept does not discuss in detail the question of how regionalism affects the development of ports. It also neglects the role played by each of the participants in the process of regionalisation and which port strategy (terminals, municipal management and port cities) should be implemented in order to control this process.

In their paper, the authors noted that there are two main directions of development of the port --as a ‘pole’ and as a ‘unit.’ Under the development of the port as a ‘pole’, the authors understand the development of the port as a ‘hub’ –

a point connecting different transportation infrastructure. From the point of view of development as a 'unit', the authors understand the port to be one specific facility, formulating trade networks of various sizes for the purpose of goods movement in the hinterland. In the proposed model, however, focus was mainly on the development of the port as a 'unit'. That means that in actual fact it was considered to be special case of development, with the characteristic of specialised container terminals involved in the process of the globalisation of trade and supply chains.

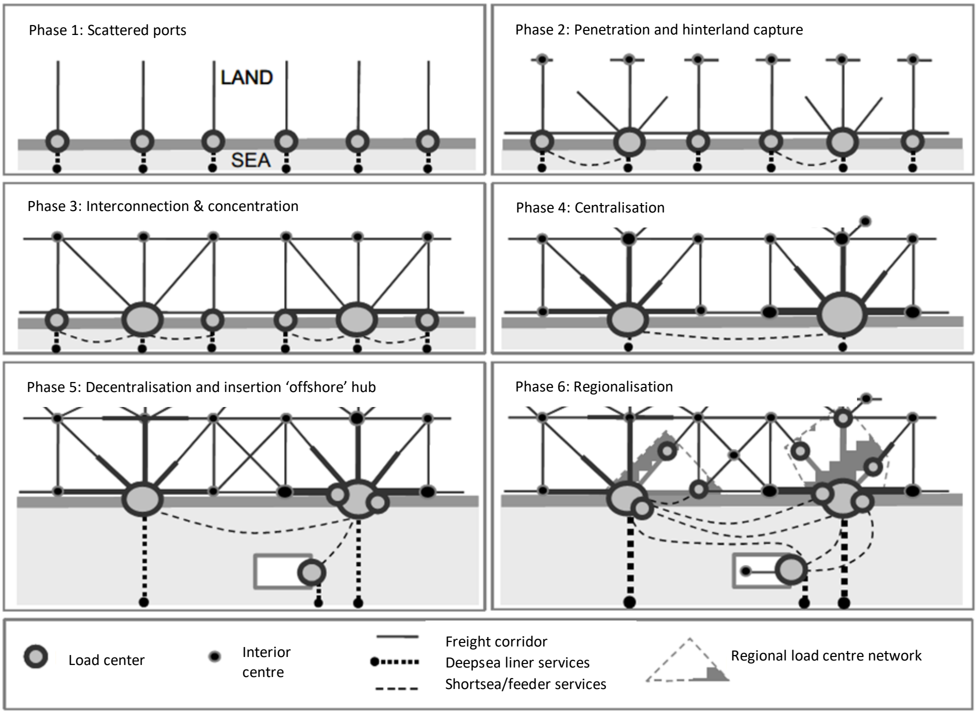


Fig. 4. Development of the Rodrigue-Notteboom model [2005].

This basic model was quickly copied by followers and imitators, over time becoming more complex and more powerful, finding harmony and intrinsic value of the theoretical constructs. At the same time, they are becoming less and less able to respond to questions about the future development of a specific port.

Gradually it became clear that the simple model of the process of port development is difficult to create. However, this is not due to a weakness of the conceptual constructs, but of the very nature of the phenomenon being studied.

2. SYNERGY AS A PARADIGM OF THE STUDY OF PORT DEVELOPMENT

A modern port complex is a high-speed, multi-level dynamic system. It is a set of interrelated elements of production that are stably integrated, and therefore cannot be adequately displayed using a simple linear system without losing its basic properties. Therefore, it is appropriate to use methodology based on synergetics to study the properties of the object. This has already proved its effectiveness in many domains of knowledge [Bushev 1994; Banachowicz, Holec and Weintrit 1996; Haken 2007; Turkmen 2014].

At the heart of the synergy is the search for common patterns of development of any system over time. Abandoning the specific nature of the systems, the synergy gains the ability to describe their evolution in a universal language. It sets up a kind of identity, or isomorphism phenomena, which can be studied using various scientific methods but with a common model, or to be more exact, moving towards a general model. Finding a unified model allows the synergy to be understood in different scientific fields.

The three basic concepts that characterise the studied systems are formed in synergy: disequilibrium, openness, and non-linearity. Openness refers to the ability of the system to exchange material (energy and information) with the environment and to have a 'source' --zones that recharge their energy environment; and 'sinks' – scattering areas with a concomitant 'discharge' of energy.

Disequilibrium is the state of an open system in which there is a change in its macroscopic parameters, such as its composition, structure, and behaviour.

The non-linear system features the property of having in its structure a variety of stationary states that correspond to different valid laws of behaviour of the system. Whenever the behaviour of these objects can be expressed in a system of equations, the equations are non-linear in a mathematical sense. Non-linearity is also seen as an unusual reaction to external stimuli, when the 'correct' exposure has a greater impact on the evolution of the system than the impact of its own trends, if they are stronger but poorly organised.

In this sense, an important achievement of synergy is the discovery of the mechanism of resonant excitation. This means that the system, in a non-equilibrium state, is extremely sensitive to the effects that agree with its own properties. Small but consistent external influences may be more effective than large influences that are less consistent.

Open non-linear systems may respond differently to the action of external forces and changing internal factors. In some cases, the system will respond by creating the strong trends and return to the old state (structure, behaviour); in other cases the system may collapse. Finally, there is the possibility of the formation of a new structure and a complete change of state, behaviour, and/or the composition of the system. Any of the above features can find their realization in the so-called bifurcation point. This is caused by the above effects, through which the system experiences instability.

The bifurcation point represents a watershed, a critical moment in the development of the system in which it selects its path. In other words, this is the point of the branching option, at which there is a disaster. In the concept of self-organisation, the ideas of being qualitative and discontinuous can be referred to using the term ‘catastrophe’.

Synergy adds a systematic approach to investigating the complex structures that are far from equilibrium. From cybernetics and systems analysis, the existence of some systems of collective interactive mechanisms is well known. As a collective, the systemic interaction of elements leads to the fact that certain components of the movement are suppressed. Thus, we should speak about the presence of negative feedbacks. Strictly speaking, it is negative feedback that creates a ‘traditional’ system [Kuznetsov and Galin 2016]. This is understood as a stable, conservative, group of members. However, when the system moves away from equilibrium, the dominant role is played by the positive feedbacks that are not suppressed, but on the contrary strengthen the individual movement of components. Small impacts become more significant the more processes are located on the macro level. Positive feedback leads to the loss of stability of the system of the organisation, as a very small deviation can have a big impact. Positive feedback loops make it possible for states far from equilibrium to add very weak deviations to the giant waves that destroy the current structure of the system and lead it towards revolutionary change – a sharp qualitative leap.

Mathematically, it can be assumed that any dynamic system, no matter what it represents, can change its settings to describe the motion of ‘representing’ the point in space called the phase. The phase space provides a convenient way to visualise the behaviour of dynamic systems. Changing the state system in time, such as with a succession of its states, can be represented by a line in the phase space – the space of possible states of the system, which is not time-dependent.

The phase trajectories (lines in phase space) allow one to see any entire set of movements that may arise under all possible initial conditions. The picture of the phase trajectory is important as an attractor, which characterises the behaviour of the system in the phase space after a certain (relatively long) time. In other words, it is a point or a subset of the phase space, which seeks all trajectories in the neighborhood of the attractor, also known as an area or a ‘swimming pool’. The trajectories, going from their initial states, eventually approach the attractors.

Attractors are a concept that refers to the active centers of potential sustainable ways of evolution of the system, and the ability to attract and organise the environment. The ‘Attractors’ theory allows us to understand the essence of complex system management. Attractors divide the space of all possible states into various areas of attraction. Once inside, a system inevitably evolves into the corresponding attractor. This is caused by the threshold nature of any external influence on the system. The impact can be effective, and will change the system trends, only if it takes the state of the system in the domain of attraction of another attractor. The closer the system is to the asymptotic stage of development, to its attractor, the more difficult it is to ‘switch’ it to another attractor. The threshold of the exposure plays a major role here. The former attractor does not let go of the system, and it is necessary to make substantial efforts to overcome the current trends, and get out of its field of attraction. Long-term, is too weak. Topologically incorrectly directed action would only be a waste of time and energy, and the system will be back on track.

3. SYNERGETIC MODELS OF PORT DEVELOPMENT

Synergy is an extremely powerful concept even if taken only as a philosophic doctrine, helping to apprehend many peculiarities of winding trajectories of port development. Still, the concept would be much more useful if it deals not with qualities only, but quantities of the processes under the study. The synergetic views over port development expressed in the descriptive paradigm are not new [Haken 2003], so this section presents some numeric models proving the feasibility of the approach as a research tool. The models below are rather simple, since the target of this paper is to discuss general ideas and not to provide exact specifications of models.

The simulation of two ports interaction

Let us consider two ports, P_1 and P_2, located on one seacoast and sharing the same ship flow $Q[t]$, where the variable t represents discrete moments of time t = 0,1,2, … .

This ship flow $Q[t]$ splits in two partial flows, $Q_1[t]$ and $Q_2[t]$, handled by the ports P_1 and P_2 respectively, so $Q[t] = Q_1[t] + Q_2[t]$.

Let us describe every port by the following values:

incoming ship flow $Q_i[t]$ (the share of Q[t] assigned to the port P_i);
ship handling resource $r_i[t]$ (the port capacity to accommodate ships);
ship queue $q_i[t]$ (the number of ships waiting in the queue for berthing);
ship handling $h_i[t]$ (the rate of ship servicing at the berths of this port);

The functional lows of the port operations we assume simple as below:

$$q_i[t] = if\{Q_i[t] + q_i[t-1] > r_i[t]\}\ then\ \{Q_i[t] + q_i[t-1] - r_i[t]\}\ else\ \{0\}$$

(if the number of ships arrived to the port and waiting in the queue the at a moment t is bigger than the port capacity $r_i[t]$, the surplus joins the queue).

$h_i[t] = if\{Q_i[t] + q_i[t-1] > r_i[t]\}\ then\ \{r_i[t]\}\ else\ \{Q_i[t] + q_i[t-1]\}$

(if the number of ships arrived to the port and waiting in the queue at the moment t is less than the port capacity $r_i[t]$ then all of them are handled, else only $r_i[t]$ of them).

Let us further assume that the shippers base their selection of ports upon two factors: the tariff for handling and the quality of service, with the latter expressed by the time ships spend in the queue waiting for berthing.

The greater the number of ships that call at port, the lower could be the tariff, due to the obvious economy of scale.

Accordingly, this first component of 'the port attractiveness' could be expressed, for example, by a simple criterion $\mathrm{N_{tar}} = \mathrm{a}/\sum_{\mathrm{i=k-T}}^{\mathrm{k-1}} \mathrm{q_i[k]}$, i.e. by a reciprocal value of the number of ships handled by the port during an interval T.

The longer is the ship queue, the less attractive is the port for the shippers. The quality of service might be expressed by a criterion$\mathrm{N_{que}} = \mathrm{b}\sum_{\mathrm{i=k-T}}^{\mathrm{k-1}} \mathrm{q_i[k]}$, i.e. by direct ratio to the total time ships spent in the queue during the interval T. The total criterion of the 'port attractiveness' for P_i in this case is $\mathrm{N_i} = \mathrm{N_{tar}} + \mathrm{N_{que}}$. The lower is the value of $\mathrm{N_i}$, the more attractive is the port P_i for shippers.

Calculated the values of $\mathrm{N_1}$ and $\mathrm{N_2}$, we could expect the distribution of the total ship flow $\mathrm{Q_i[t+1]}$ in reciprocal ratio: the port P_2 will have the share $\frac{N_1^{-1}}{\sum_1^2 N_i^{-1}}$ and the port P_1 will have the share $\frac{N_2^{-1}}{\sum_1^2 N_i^{-1}}$ of the ship flow, or $Q_1[t+1] = \frac{N_2^{-1}}{\sum_1^2 N_i^{-1}} \cdot Q[t]$ and $Q_2[t+1] = \frac{N_1^{-1}}{\sum_1^2 N_i^{-1}} \cdot Q[t]$.

If $[t] = const = Q_0$, then the partial flows will have static values, specifically $Q_1 = \frac{N_2^{-1}}{\sum_1^2 N_i^{-1}} \cdot Q_0$ and $Q_2 = \frac{N_1^{-1}}{\sum_1^2 N_i^{-1}} \cdot Q_0$.

If $Q[t] \neq const$, the situation will be dynamical. In order to study it and for the sake of simplicity, let us assume that $[t] = a \cdot t + b \cdot t \cdot \sin(C \cdot t + D)$.

The behaviour of the partial flows $Q_1[t]$ and $Q_2[t]$ in this case illustrates (Fig. 5).

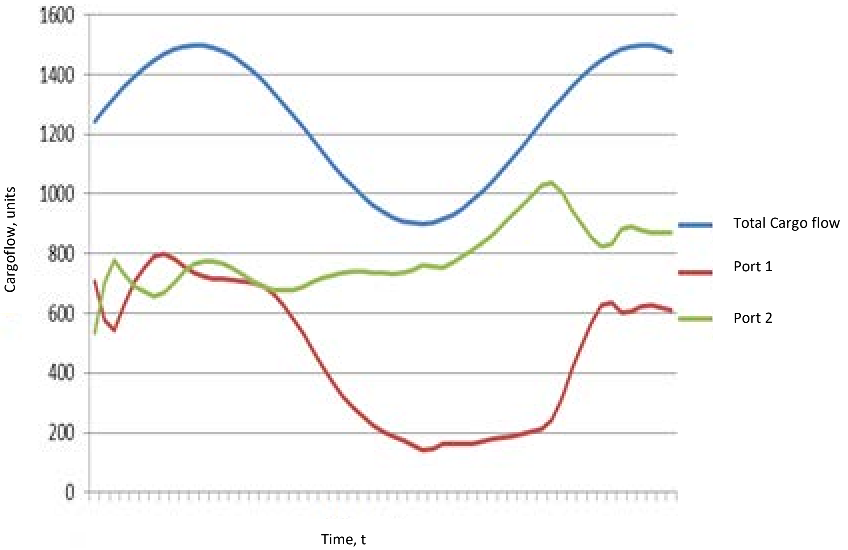


Fig. 5. Model behaviour of port interaction

The portrait of the system against the phase plane is represented in Figure 6.

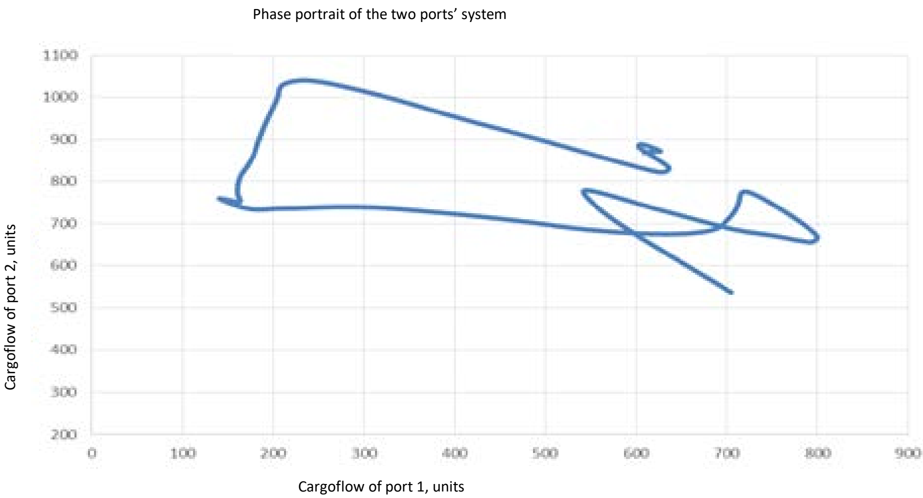


Fig. 6. The portrait of the system against the phase plane represents

The simulation of three ports' interaction

The same procedure as described earlier can be done for three ports. The results are illustrated at Figure 7. As with the two-phase portrait, it must be done in a three-dimensional system – Figure 8.

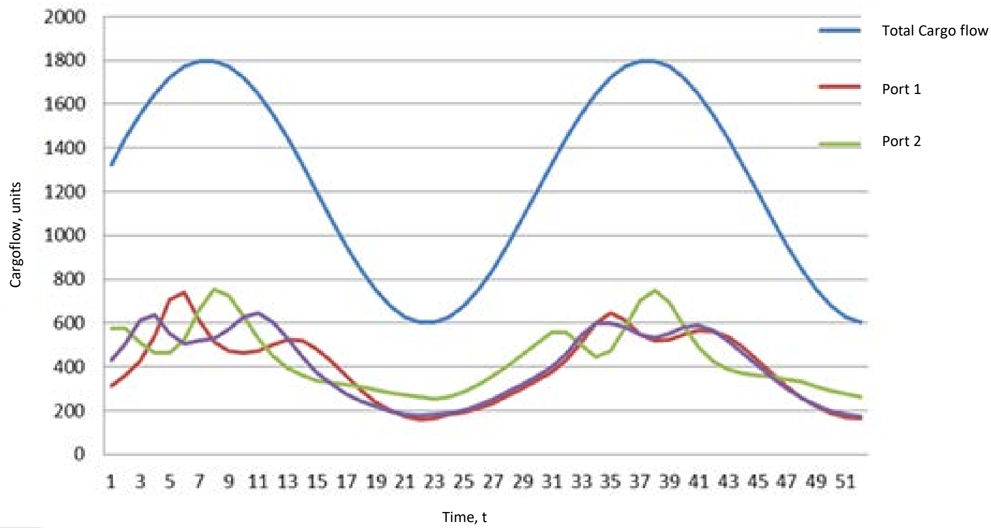


Fig. 7. Model behaviour of ports' interaction

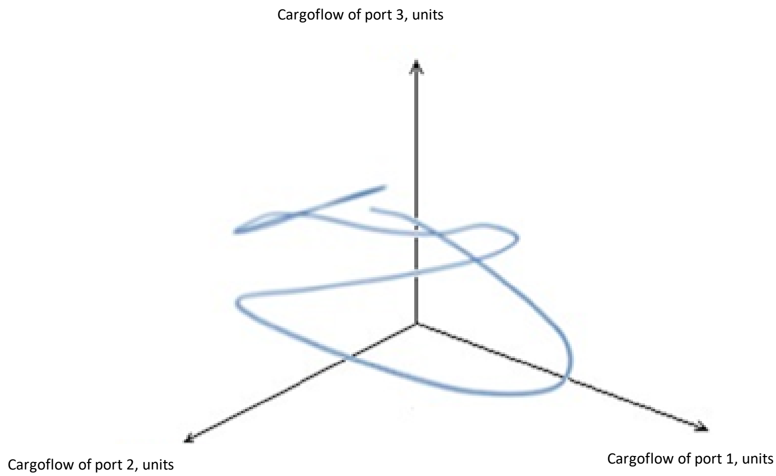


Fig. 8. The portrait of the system against the phase plane represents

Port population development. Let us assume that at the moment we have a population of ports located along a sea coast of the cargo catchment area with the potential cargo flow Q. This cargo flow provides the amount of operations supporting the existence of n ports. Let us introduce a new variable $\boldsymbol{x_t} = \frac{\boldsymbol{n_t}}{\boldsymbol{n}}$, where $0 \leq \boldsymbol{x_t} \leq 1$ and n_t is the number of ports existing in the moment t.

Suppose that we register the size of population once in a year. The cargo handling in ports generates a certain profit enabling the building ofnew ports, so the size of the next population $\boldsymbol{x_{t+1}}$ is a linear function of the current value $\boldsymbol{x_t}$, i.e. $\boldsymbol{x_{t+1}} = \boldsymbol{r} \cdot \boldsymbol{x_t}$. Here $\boldsymbol{r}$ is the rate of the population's growth.

At some point of the growth the potential cargo flow Q is exhausted, thus stopping the growth. It is natural to expect that the bigger is population $\boldsymbol{x_t}$, the lower is the rate of the population's growth. The simplest way to take it into account is to replace $\boldsymbol{r}$ with $\boldsymbol{r} \cdot (1 - \boldsymbol{x_t})$. The growth $\boldsymbol{x_{t+1}} = \boldsymbol{r} \cdot (1 - \boldsymbol{x_t}) \cdot \boldsymbol{x_t}$ is called 'logistical parabola'. The condition of $0 \leq \boldsymbol{x_t} \leq 1$ stays true within the interval 0 < r < 4.

While r <1 the population of ports cannot survive, whatever is its initial value (Fig. 9)

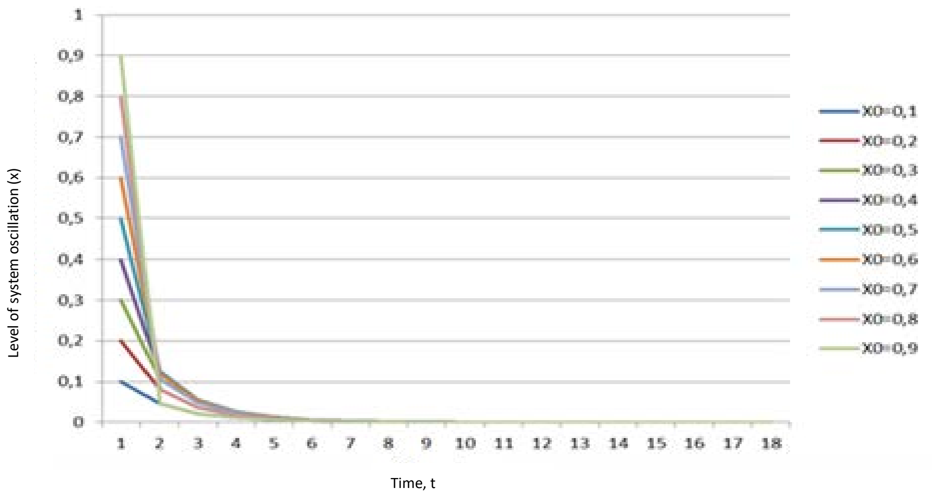
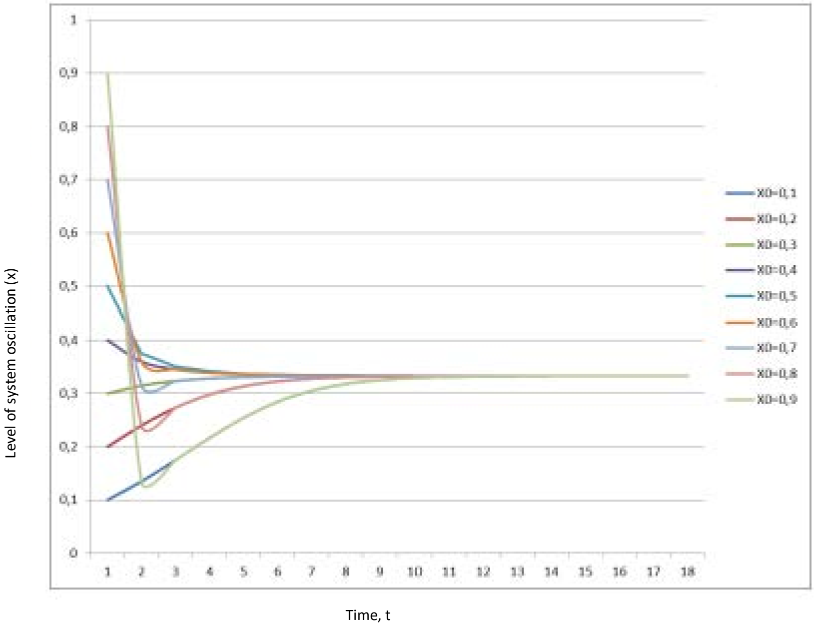
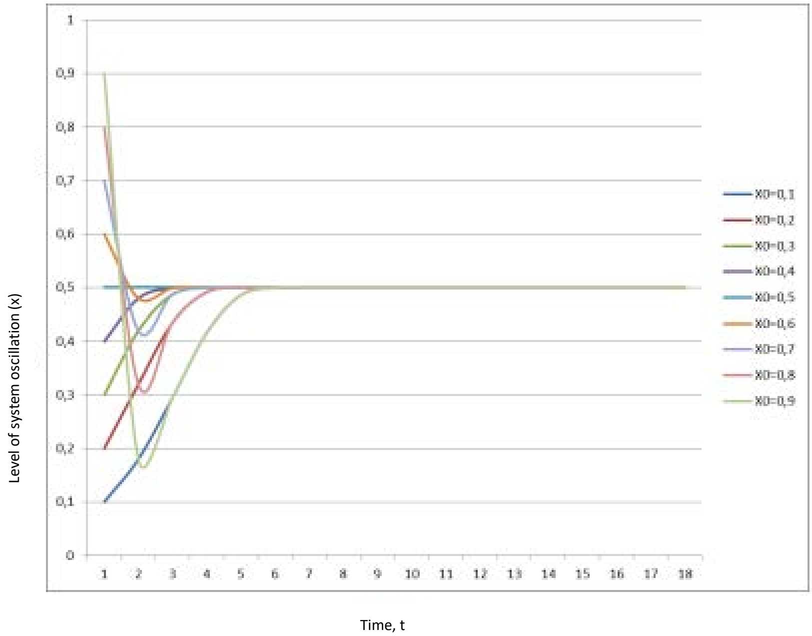


Fig. 9. Population's deterioration with r < 1

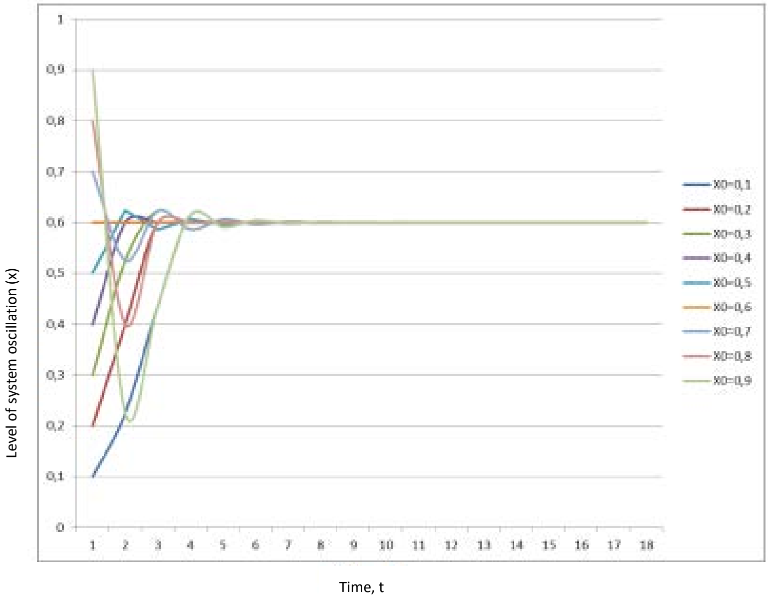
With 1 < r < 3 the model shows a certain equilibrium point, whatever is its initial value (Fig. 10, a-c). The attractive force to the equilibrium state is the bigger with the growth of r.


Level of system oscillation (x)
Time, t
X0=0,1
X0=0,2
X0=0,3
X0=0,4
X0=0,5
X0=0,6
X0=0,7
X0=0,8
X0=0,9

a)


Level of system oscillation (x)
Time, t
X0=0,1
X0=0,2
X0=0,3
X0=0,4
X0=0,5
X0=0,6
X0=0,7
X0=0,8
X0=0,9

b)



c)

Fig. 10. 'Attraction' to the stable population with r = 1.5; 2.0; 2.5 (a-c)

But in the neighborhood of critical point $r \approx 3$ the port population starts to oscillate between two different equilibrium points. So, with $r = 2{,}6$ «the cycle of first order» appears, an equilibrium point with $x = 0.6154$ (Fig. 11).

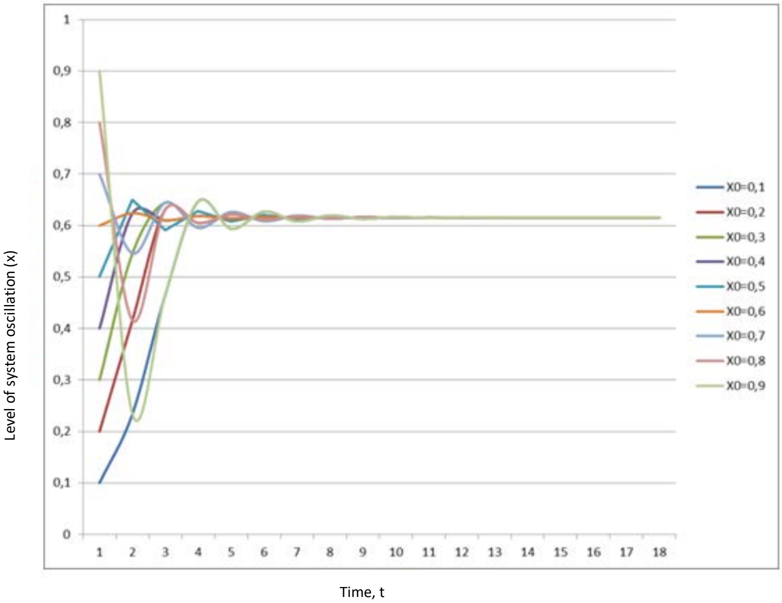


Fig. 11. A stable population with r = 2.6

With r = 3.1 «the cycle of second order» appears, when population oscillates (periodically repeat its values) between x = 0.5582 and x = 0.7645 (Fig. 12).

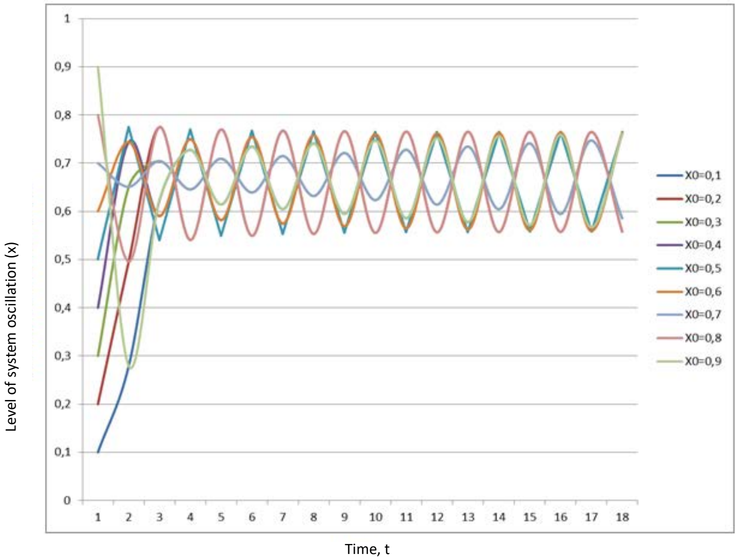


Fig. 12. Oscillation of population among two levels with r = 3.1

But in the neighborhood of critical point $r \approx 3$ the port population starts to oscillate between two different equilibrium points. So, with $r = 2.6$ «the cycle of first order» appears, an equilibrium point with $x = 0.6154$ (Fig. 13).

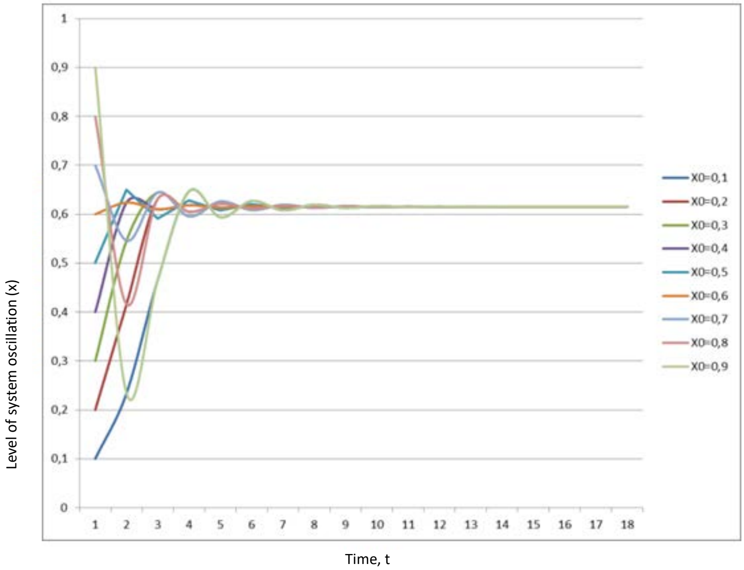


Fig. 13. A stable population with r = 2.6

With r = 3.1 «the cycle of second order» appears, when population oscillates (periodically repeat its values) between x = 0.5582 and x = 0.7645 (Fig. 14).

This phenomenon is a classical sample of bifurcation. With the growth of r the behaviour is more and more complex: two levels splits into 4, then 8, then 16, 32, … levels and eventuates in total chaos.

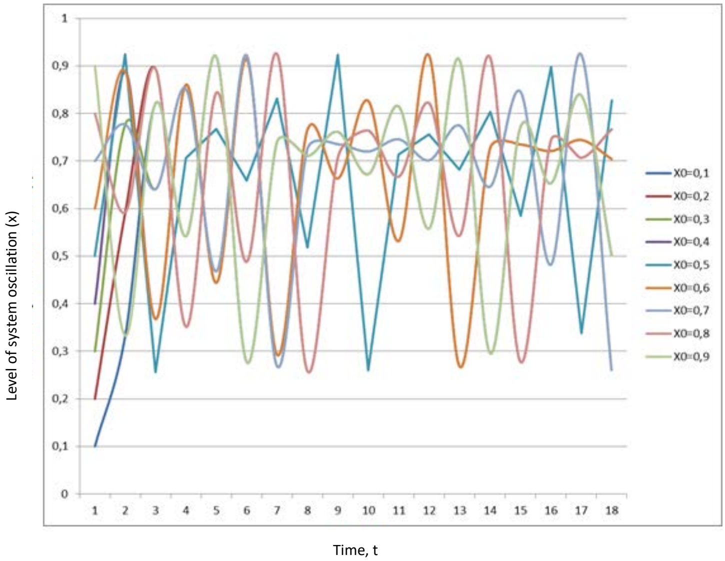


Fig. 14. Oscillation between multiple levels

The resulting levels usually are represented by bifurcation diagrams in the plane of *x*-*r* (Fig. 15).

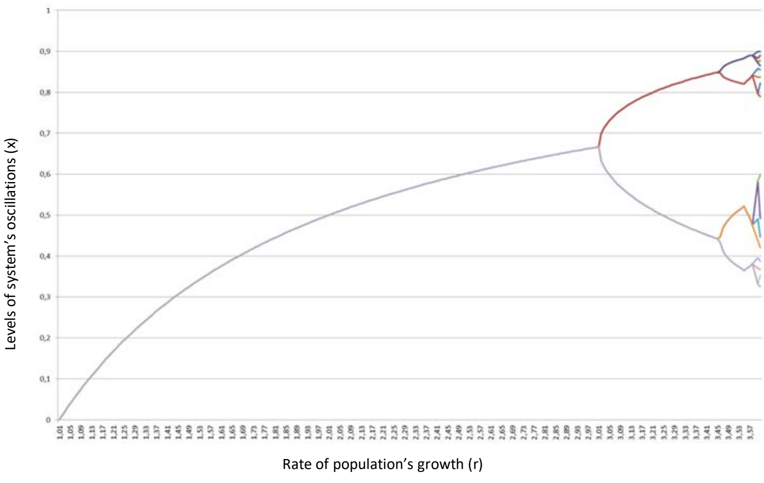


Fig. 15. Bifurcation diagram for port population

The models discussed above can be very easily recognised: they could be found in many different studies dealing with synergy. The reason to include them in this paper is simple to prove that this paradigm is fully applicable to the port development domain. The models produce quantities results to some extent. Before the further discussions, as the classical simulation approach assumes, there should be descriptive models explained the developing of two ports, Barcelona and St. Petersburg, in accordance with synergy development principles.

St. Petersburg port. Points of bifurcation. An example of such bifurcation points can be seen in two points in the history of the port of St. Petersburg:

A) The resolution of 1721 of the Senate of the Russian Empire on the concentration of export cargo in the port of St. Petersburg, which meant that St. Petersburg was the major port of the Russian Empire for the next century [Mesnjakov 2002].

The founding and development of the St. Petersburg port happened in fierce competition with the principal Russian port of the time, Arkhangelsk. Trade in the years from 1716–1719 is shown in Table 3.

Table 3. Ship calls to both ports in 1716–1719

Years	Arkhangelsk	St. Petersburg
1716	208	33
1717	146	51
1718	116	54
1719	119	33

At the end of the Great Northern War, Peter I instructed the Senate to issue a decree on the concentration of export products in St. Petersburg. As a result, the previously intensive commercial activity of the Arkhangelsk City Exchange collapsed, as noted in Table 4.

Table 4. Ship calls to both ports in 1722–1725

Years	Arkhangelsk	St. Petersburg
1722	60	119
1724	22	240
1725	19	236

B) The historic decision to build a Sea Canal in the middle of the 19th century in the port of St. Petersburg, which ensured that it became the leader among Baltic Russian ports up to 1917 and beyond.

By the mid-19th century, with the increase in the number of ships calling at St. Petersburg's port, it had become virtually impossible to handle vessels on the Spit of Vasilyevsky Island, and even more difficult to carry out loading and unloading operations in relatively small areas. With the increasing size of ships, the progress of vessels to the Spit became quite difficult. This was compounded by the construction of a bridge in the lower reaches of the Neva. In most cases vessels could not proceed through the stretches of the Neva known as the Nevsky bar. Therefore, the creation of additional transhipment platforms in Kronstadt was required.

Vessels with significant draft went to berths at Kronstadt, where the goods were loaded onto barges and transported to St. Petersburg. The depth on the Nevsky bar does not exceed three meters, and at low water can be as little as 2.5 meters. Of 2,600 ships annually arriving at Kronstadt in the middle of the 19th century, no more than half could traverse the Nevsky bar. The other half, carrying more than two thirds of the total cargo, were forced to stop in Kronstadt due to their size, and offload goods onto barges. This system of the delivery of goods led to additional costs because of double loading, damage, and loss of goods (for example, in the case of loading and transportation of coal in this way, 4 to 8% of the total was lost).

During the second half of the 19th century, the port of St. Petersburg had some serious competition. To illustrate the competitive situation, statistics for the decade from 1865–1874 are shown, and they are quite revealing. During these years, traffic through St. Petersburg fell. Outgoing goods (exports) from Russia to Europe through St Petersburg fell from 28 to 20.9%, and incoming goods (imports) fell from 43.6 to 27.7% (Fig. 16).

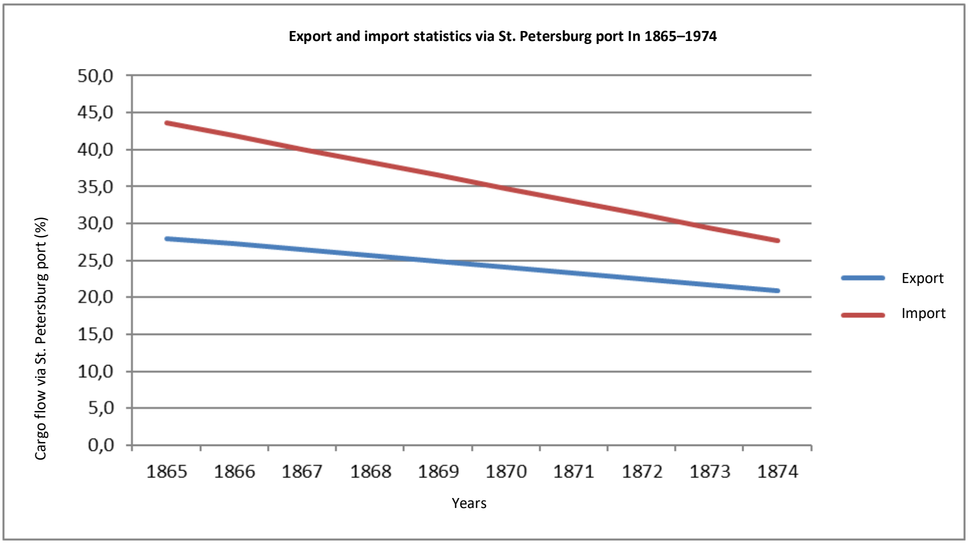


Fig. 16. Export and import statistics via St.Petersburg port

In order to avoid unnecessary congestion, goods started being discharged in Reval (Tallinn) and Narva, and then on the Baltic railway heading deep into Russia. For example, if prior to 1868 in Revel, goods were unloaded to the value of 600,000 to 800,000 rubles, then from 1869, the amount exceeded one million rubles and more. The dynamic was as follows: 1869 – 1.4 m; 1870 – 3.6 m; 1871 – 13.7 m; 1872 – 32.6 m; 1873 – 21.1 m; 1874 – 40.6 m. A similar pattern was observed in the port of Narva, where cargo turnover for the same period increased from 1.5 to 4 million rubles (Fig. 17).

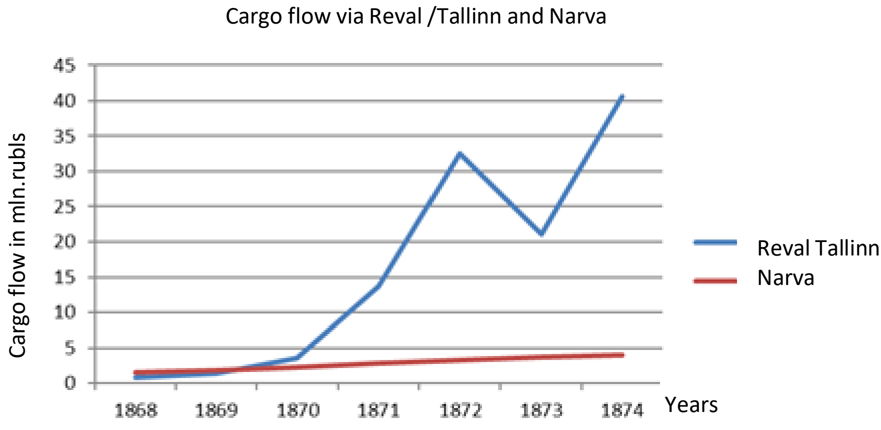


Fig. 17. Cargo flow via Reval /Tallinn and Narva

Therefore, there was a choice between the three ports of St. Petersburg, Revel and Narva [Kuznetsov and Galin 2015b]. After a decision was made in favour of the Port of St. Petersburg, dredging work began, and a marine canal was completed from the island of Kotlin to the mouth of the Neva River in 1885. At the mouth of the Neva, major dredging works were also carried out, which led to the construction of three harbours. A small pool at the start of the fork of the channel levees (‘Sea Pier’), and customs at the entrance of the harbour channel from the Neva (‘Gutuevsky Port’) were created in 1885.

The third harbour, servicing the shipment of timber products and crops from abroad, was constructed during the period from 1897 to 1907, and was named ‘Wheat-Forest’ (Fig. 18). Thus, the port of St. Petersburg became the leading Russian port on the Baltic Sea.

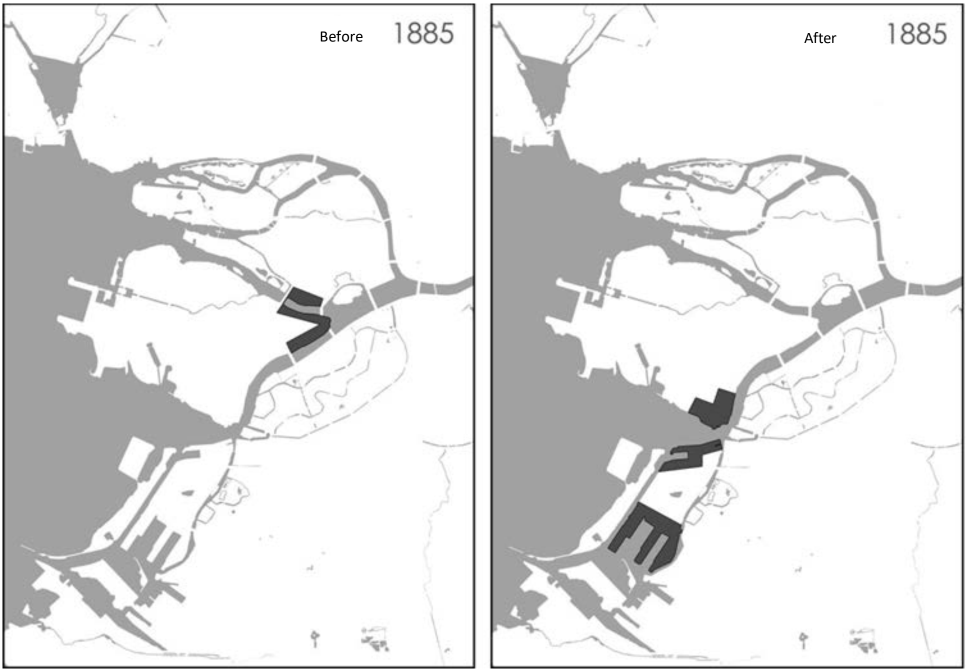


Fig. 18. Schemes of St. Petersburg port

4. CONCLUSIONS

Within the modern science of transport management, it is important to form a clear picture of its synergetic relationship with the world. The essence of synergetic control is the ability of complex nonlinear systems to 'build themselves'. All that is needed is the correct initiation of the desirable social trends in this system of self-development.

Based on the idea of the existence of synergistic 'field development paths, the spectrum of structures, potentially contained, hidden in nonlinear media', and the role of humans in the world, we can say the following.

- Since every type of diverse development can grow following its own path, there is always the chance to not only select the best way, but also to manage it.
- While there are a large number of paths, this number is not infinite, and one can always try to establish specific system limitations the exclusion principle, narrowing the space when searching for possible paths.
- There is in principle a possibility to describe and calculate the optimal and realistic terms of available capacity, as well as the proposed mechanisms for their implementation.

- Knowing the desired future situation and the ways to follow the natural tendencies of self-organising systems, one can reduce time spent on the attractor, or the future form of the organisation.

Following the concepts of synergy in particular ports, or in the transport and logistics environment in general, it should be regarded as a super self-organising, open, non-linear system, with all the associated properties, laws and principles of development.

REFERENCES

Banachowicz, A., Holec, M., Weintrit, A., 1996, *Synergistic Approach to the Integrity of Navigational Systems*, 3rd Saint Petersburg International Conference on Integrated Navigation Systems, Saint Petersburg, Russia.

Beresford, A.K.C., Gardner, B.M., Pettit, S.J., Naniopoulos, A., Wooldridge, C.F, 2004, *The UNCTAD and WORKPORT Models of Port Development: Evolution or Revolution?* Maritime Policy & Management, vol. 31, no. 2, pp. 93–107.

Bird, J., 1980, *Seaports and Seaport Terminals*, Hutchinson University Library, London, UK.

Bushev, M., 1994, *Synergetics: Chaos, Order, Self-organization*, World Scientific Publishing Co., Singapore.

Haken, H., 2003, *Secrets of Nature. Synergistics: Science on the Interaction*, IKI, Izhevsk, Russia.

Haken, H., 2007, *Information and Self-Organization a Macroscopic Approach to Complex Systems*, Springer Verlag – Berlin – Heidelberg, Germany.

Kuznetsov, A.L., Galin, A.V., 2015a, *Spatial Development of Ports*, Innovations, vol. 2, no. 208, pp. 115–120.

Kuznetsov, A.L., Galin, A.V., 2015b, *The Genesis of Port Development Models in Modern Transportation Science*, Vestnik Gosudarstvennogo Universiteta Morskogo i Rechnogo Flota imeni admirala S.O. Makarova, vol. 2, no. 30, Saint Petersburg, Russia.

Kuznetsov, A.L., Galin, A.V., 2016, *Cybernetic Method of Management of Development of Sea Ports*, Vestnik of Astrakhan State Technical University, Series: Marine Engineering and Technologies no. 3, pp. 93–97, Astrakhan, Russia.

Mesnjakov, A.L., 2002, *History of the City*, Izdatelstvo Aleksandr Print, Russia.

Notteboom, T.E., Rodrigue, J.-P., 2005, *Port Regionalization: Towards a New Phase in Port Development*, Maritime Policy & Management, vol. 32, no. 3, pp. 297–313.

Turkmen, O., 2014, *Synergetic Theory of Life: Nature, Algorithm, Self-insight*, *Conscious Evolution,* Troubador Publishing Ltd, Leicester, UK.

UNCTAD, 1985, *Port Development*, New York, USA.

UNCTAD, 1992, *Port Marketing and the Challenge of the Third-Generation Port*, Geneva, Switzerland.

Van den Berg, R., De Langen, P.W., 2011, *Hinterland Strategies of Port Authorities: A Case Study of the Port of Barcelona*, Research in Transportation Economics, vol. 33, no. 1, pp. 6–14.