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Migration of container terminals as their natural process of evolution: case study of Gdańsk and Gdynia ports.

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Abstract

The paper proposes a theoretical model of container terminals and container port development, based on the life cycle theory, threshold theory and catastrophe theory, and in references to Kuznets' swings (interpreted as waves of infrastructural investments), and Kondratiev long economic waves.

The aim of this model is to explain the development process of a container terminal and a port within one technological generation, as well as in intergenerational configuration, and relate it to the migration process of container terminals in the scale of a port-city urban area. Then, the applicability of this model was checked in the case of the container ports in Gdynia and Gdańsk (Poland). The analysed evolution process of ports of Gdynia and Gdańsk conforms with the proposed theoretical model, proving that the migration of container terminals within these ports is a part of their natural process of evolution, being a consequence of their threshold development and location splitting.

Considering the physical location of development investments within the container ports of Gdańsk and Gdynia, it was noticed that there are two basic directions of migration of container terminals. One is the migration of the port's main container activity (core terminal or terminals), being a result of a generational change taking place after overcoming the maturity point. The second type of migration is connected with dispersion of port development investments in the increasingly distant port hinterland, caused by the need of the life extension of terminals within one technological generation.

In an analogy to the processes of development of living organisms, we can treat the migration of terminal outsourced functions as a “vegetative” increase, being an attempt to extend the life of the terminal, while the migration of the core terminal within the port area (erecting a new generation terminal) can be treated as “generative” growth.

Introduction

Currently, to be fully operational a container terminal must consist of a system of logistic and technological objects, situated on its close hinterland (Wilmsmeier et al. 2011, OECD 2014, Notteboom 2010 and 2016, Monios 2017, Ye et al. 2018). These external facilities accompanying a single container terminal within a port’s metropolitan region, often occupy a much larger area than a terminal itself.

The spatial elements of a container port usually creates a dynamic, discontinuous structure, such as for example, the ports of Rotterdam, Antwerp, Hamburg, Hong Kong, Busan or Singapore. They expand simultaneously both towards sea and land (Klink 1997, Slack 2007, Notteboom and Rodrigue

2009, Ng and Gujar 2009, Cullinane and Wilmsmeier 2011, Hall and Hesse 2012, Monios and Wilmsmeier 2013). Some new terminals emerge within the port's structure, whilst some disappear (Merk 2018). The reason for this phenomenon is the specificity of a container terminal and port's evolution.

This paper supports the concept that the migration pattern of container terminals within a port metropolitan area is an imminent feature of their natural process of evolution resulting from their technological life cycles and investment thresholds, resulting from the changes in their foreland, hinterland, and within container ports themselves.

The research on spatial evolution of container terminals and ports is mostly based on the spatial analysis of Gdańsk and Gdynia (Poland). However, preliminary studies of other European container ports (Antwerp, Rotterdam, Hamburg) show that the phenomenon of spatial evolution of these ports follows analogous principles.

The evolutionary approach to the topic, required the studying of port handbooks, cartographic materials (e.g. city plans, navigation charts), and earlier literature, such as: Oram (1965), Burg van den (1969), Quinn (1972), Frankel (1987), PIANC (1987), UNTCAD (1985, 1991a, 1991b, 1992). Contemporary transformation of container ports demanded the review of contemporary technologies available in container ports (Wang et al. 2019, [17], [18] [19]).

The time frame for the research starts in 1956 and extends until 2020. However, the development of port case studies (Gdynia and Gdańsk) is considered respectively between the years 1969-2020 and 1998-2020.

The work proposes a qualitative model describing the principles of the spatial evolution of a container terminal within a port and its hinterland, chiefly based on the theory of life cycle (Rogers 2003), threshold analysis (Malisz 1970) and the cyclicity in maritime transportation (Rodrigue et al. 1997). The purpose of this theoretical model is to explain the development process of a container terminal within one technological generation, as well as between generations, and relate to the migration process of container terminals in the scale of a port-city urban area. Then the applicability of this model was checked for the container ports in Gdynia and Gdańsk.

The paper, after characterising the theoretical framework for building the model, refers to the development process of a container terminal within one generation, and then it addresses the intergenerational process of container port development. Next, the case study of the ports of Gdańsk and Gdynia is considered in light of the proposed model. Finally, the graphical model of the migration of subsequent generations of container terminals in the scale of a port-city urban area is presented.

Theoretical framework

The paper proposes a theoretical model of container terminals and container port development, based on the life-cycle theory (Rogers 2003), threshold theory (Malisz 1970, Kozłowski and Hughes 1967) and partially on the catastrophe theory (Thom 1975). It also makes references to Kuznets' swings, interpreted as waves of infrastructural investments, and Kondratiev long economic waves (Korotayev and Tsirel 2010).

The evolution of container ports and terminals can be considered from a perspective of the product of the life-cycle theory, as a process of adopting innovations and the diffusion of innovations (Rogers 2003, Kotler et al. 2005, Liefner and Schätzl 2017). It could be considered within the lifetime of a single terminal (this approach was used in the work of Wilmsmeier and Monios (2020) while referring to intermodal terminals), or to the whole process of containerisation (Guerrero and Rodrigue 2014), reflected in the spatial structure of a container port (Jeevan et al. 2021). In both situations a life cycle approach aims to identify the competitive strategies optimal for a particular stage of life (Cullinane and Wilmsmeier (2011), Monios and Bergqvist (2017)). Considering the life cycle of intermodal terminals, Wilmsmeier and Monios (2020) defined three development strategies extending their activity in time: physical restructuring (e.g. terminal expansion), operational reorganisation (e.g. redesign of the terminal) and institutional reorganisation (e.g. introducing of new business models). In this paper only the first two methods were considered, as influencing the spatial development patterns. Recently, Jeevan et al. (2021), while exploring the structure of Malaysian container seaport life cycles, described the concept of container seaport life cycles in depth.

Threshold theory deals with the explanation of the emergence of breakthrough points in the dependencies between the cost function and the expansion function of spatial structures, as well as on the consequences of the breakthrough points existence for the processes of spatial development (Malisz 1970, Kozłowski and Hughes 1967). Such points occur when the normal operating conditions under which the investment generates the so-called fixed costs, turn into more complex conditions, causing the need to incur additional costs – the so-called threshold costs – necessary to overcome for further development. This phenomenon results from the indivisibility of infrastructure investments. The moment of the appearance of additional costs is called the investment threshold (or the development threshold) and it constitutes a limitation of the continuity of the spatial structure development process (Kozłowski 1973, p. 57). The investment threshold may be gradual or leap-like (Kozłowski 1973, p. 77). The gradual thresholds are associated with incurring relatively small outlays, are usually associated with the need to expand or modernise the facility. Leap-like thresholds are connected with the necessity to incur significant costs at one time and are often associated with a structural change or even creation of a new quality - a new generation facility. The development of container terminals should therefore be considered from both perspectives: as a development within one generation, within which there are gradual thresholds occurring, and as an intergenerational development, where the leap-like thresholds appear between particular generations.

The generational change between technologies used in container ports is a discontinuous transition from one technological quality to another one. Thus, the Thom's theory of catastrophe (1975) is helpful in explaining this leap-like threshold and occurrence of the S-curve pattern of innovation. Moreover, the cyclicity of technological generations of container terminals is related with the Kuznets' swings and long economic waves of Kondratiev (Korotayev and Tsirel, 2010) - the cyclic behaviour of containerisation, and container ports, was already proven among others by Guerrero and Rodrigue (2014). This concept is also supported by the literature referring to the diffusion of containerisation (Notteboom and Rodrigue, 2009; Rodrigue, Comtois and Slack, 1997) and indirectly by older literature referring to port development models by Bird (1971), Hayuth (1981), Hoyle (1989).

The development process of a container terminal within one generation

Wilmsmeier et al. (2011) define port development as a continuous, cumulative process that recurs as a series of innovations. However, these authors emphasise the need to distinguish between the process of "growth" and "structural change". The development of container terminals should be treated analogously - as the sum of quantitative (growth) and qualitative (structural) changes. In this case the development of container terminals was considered parallel in two main areas: spatial and organisational (Fig. 1).

The development of container terminals, according to the principle of least effort (Zipf 2012), usually takes place in order from the simplest changes (requiring the least effort to overcome the development threshold) to the most complex changes (requiring the greatest investment effort). As a consequence of this process, the forms resulting from evolution are increasingly complex. There are four basic stages in the development of any generation container terminals (Fig. 1, Fig. 2):

- **Simple continuous growth** of a terminal consists of increasing its surface of land and water area (A) or increasing the storage heights (B). Simple growth can take place, for example, by including the adjacent surface within the terminal, or by increasing the number of tiers in the container yards through the use of devices with greater handling capabilities (e.g. the use of higher RTGs (rubber tired gantry cranes) or SCs (straddle carriers), or the introduction of multi-level platforms for handling refrigerated containers).

- **Simple discontinuous growth** (i.e. **complex growth**) manifests itself in outsourcing some of the functions performed in the main part of the terminal to areas located in its well-connected vicinity or further hinterland (C) such as construction of container depots, technological yards, car parks for trucks or dry ports. It may also consist of reducing the container handling time in the terminal (D), by, for example, reorganising the work of the terminal gate, introducing a new operating system etc. In the first case it is a spatial discontinuity, in the second it is a kind of time discontinuity. In case of simple discontinuous growth, the container terminal development consists of increasing the terminal capacity while maintaining a constant area of the main part of the terminal and transferring some of its functions outside. This type of development is called location splitting (Liefner and Schätzl 2017). Giving just a few examples of the location splitting phenomenon, the ports of Rotterdam (Maasvlakte 2), Busan (Busan New Port Container terminal), Guangdong (Shanghai) can be mentioned. According to Rodrigue et al. (2010), the development strategy based on the location split is a manifestation of the maturity of the object. Based on the product life cycle theory, Liefner and Schätzl (2017), Wilmsmeier et al. (2011), and Wilmsmeier and Monios (2020) found that the spatial discontinuity is a way to extend the life cycle of port terminals, when the maximum level of investment of a terminal within its limits has already been reached. This phenomenon is illustrated in Figure 1 and Figure 2. As a result of the spatially discontinuous growth of container terminals, the regionalisation process intensifies, which is manifested in the integration of port terminals with their distribution network both on the hinterland and foreland, and the systematic transfer of port and logistics activities to functional areas of a port metropolitan area (Notteboom and Rodrigue 2005, Rodrigue and Notteboom 2010).
- **The structural change** is related either to the transformation of the internal structure of the terminal by using new technologies (the process of terminal "pupation" into an object representing a new technological quality and higher capacity which occurs within its existing borders), or with the transfer of the complete terminal to another location having larger area - in this case relocation is not related to a change in technology. Changing the functional and organisational structure and handling technology within an existing terminal area (F) is troublesome and cost-consuming, as it causes the temporary limitation of the terminal's activity, without guaranteeing the final possibility of applying solutions optimal for a given technology. For this reason, a complete reconstruction of the structure of an existing container terminal to the full extent is relatively rare and takes place only when a completely new high-performance container handling technology is available. It is even more rare to relocate the terminal using the technology typical for the existing terminal (E).
- **New generation** consists of a combination of both previously mentioned development forms (E+F). Therefore, it is the result of the construction of a terminal representing an entirely new technological structure, whereby having greater capacity and being situated in a new location (independent of the old terminal, with better accessibility from water and land, and on a much larger area). Many container port operators are now choosing to expand by building a new terminal located on artificial piers or islands. This is due both to the possibility of obtaining space on the water with appropriate surface and depth conditions, as well as the desire to avoid ownership problems. Interestingly, along with new generation container terminals, external transport and logistics facilities coupled with their activities are also being built in the close hinterland. This phenomenon can be explained by the fact that functions, once outsourced from terminal during their evolution, no longer return to the main area of a terminal.

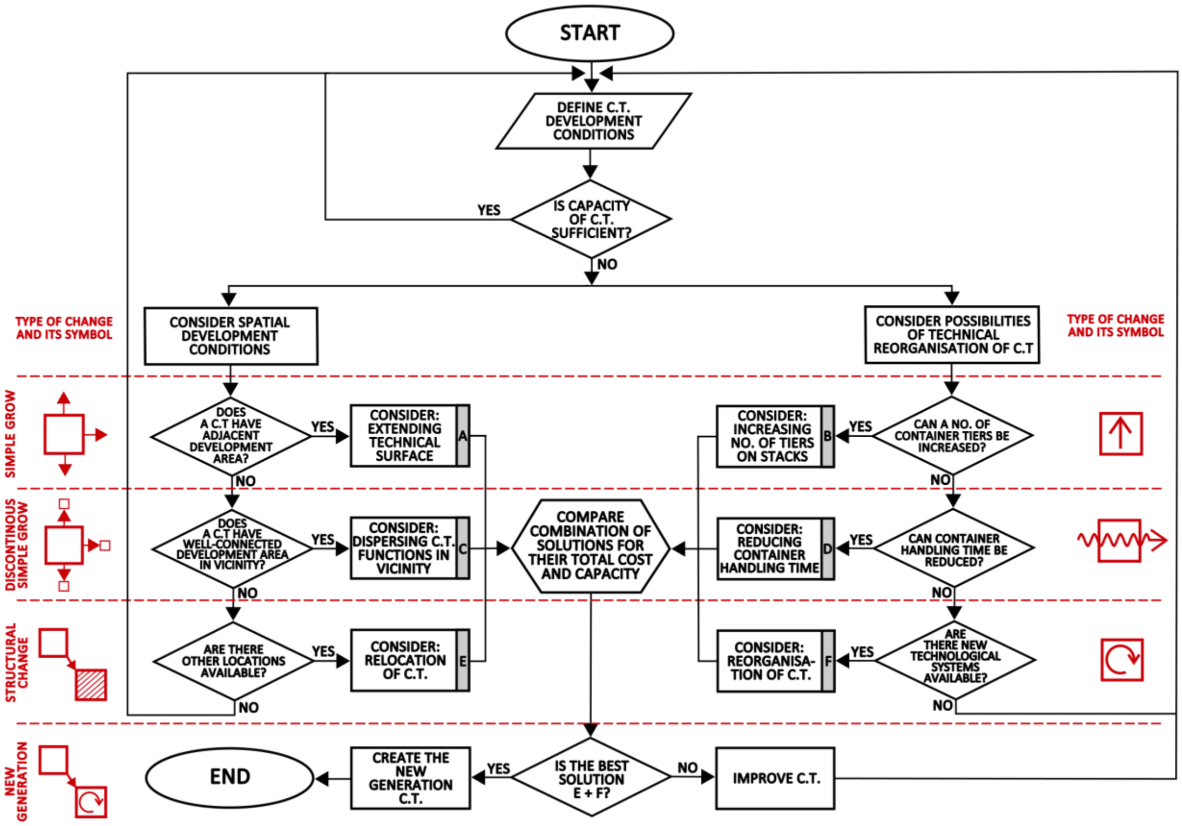


Fig. 1. Semi block-diagram explaining the decision process while developing a container terminal (C.T.). Source: own elaboration.

The decision-making process (Fig. 1), carried out in the situation of a container terminal capacity deficit, takes into account the possibility of considering more than one solution simultaneously. The order of making decisions results from the existing local conditions (such as the availability of space for further development, or the availability of newer technologies etc.) and from the level of expenditure required to implement a given solution. For this reason, implementation of solutions is usually analysed in subsequent stages, starting with a simple growth, through complex growth, structural change, and finally, with a new generation terminal. For example (Fig.1), in the first attempt, equivalent solutions are: A, B, A+B, or no investment (0). In the next attempt, the solutions of the first stage are considered, and then: C, D, C+D, 0, A+C, B+D, A+B+C, A+B+D, A+C+D, B+C+D, A+B+C+D etc.

Fig. 2 shows the theoretical relation between the increasing needs for capacity of a container terminal (CT1) and the investments necessary to enable further work of a terminal, and handling the expected volume of cargo. The optimum investment strategy allows for a smooth growth of a terminal's capacity. In this case the development function takes a form of the bell curve (its rising part). In reality the development of the container terminal is usually connected with some investment delays (curve of delayed development in Fig. 2), where each leap of the curve explains overcoming an investment threshold. Therefore, container terminals are usually in one of two states at a given moment - underinvestment or overinvestment in infrastructure (Cullinane and Wilmsmeier 2011). When a container terminal of a new generation occurs within a port's borders (CT2), the development curve of the existing terminal (CT1) falls down (the descending part of the bell curve in Fig.2). At the same time the development function of a new generation terminal (CT2) starts growing (Fig. 2). As a result, the capacity of both terminals is the sum of both curves (increasing CT2 and decreasing CT1) and in this section it takes the form of a S-shaped curve.

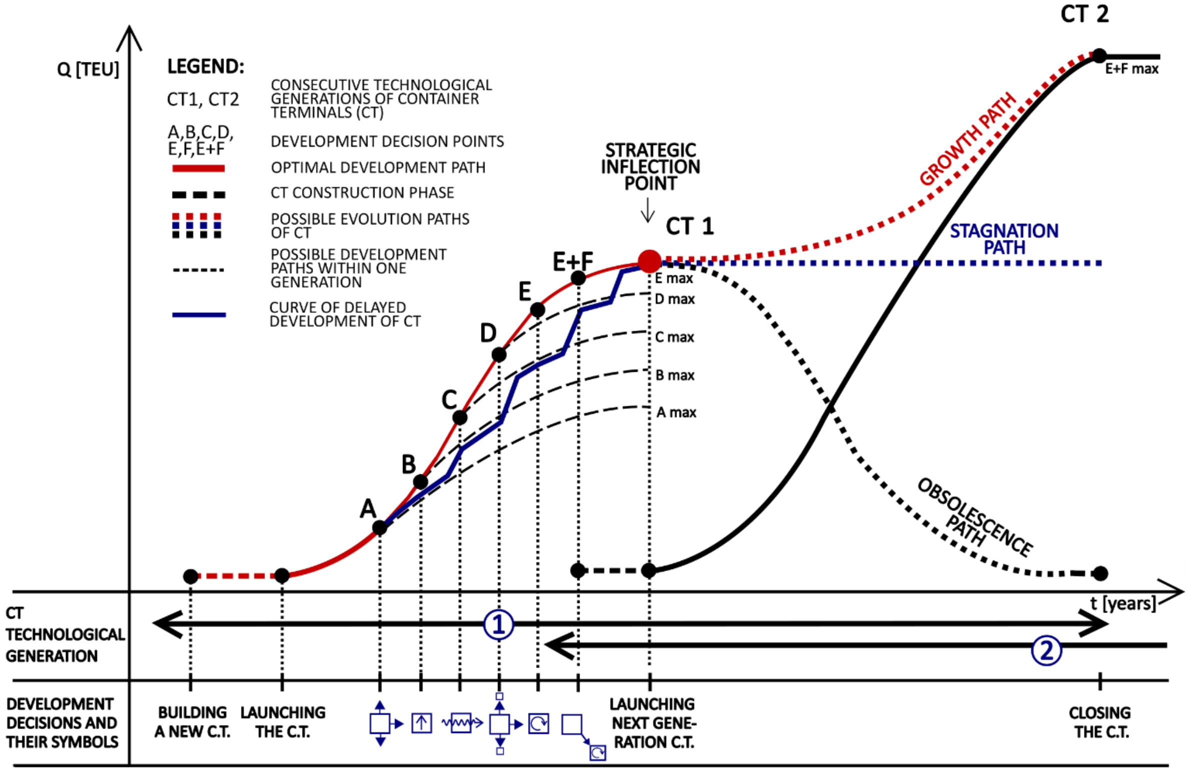


Fig. 2. Theoretical model of container terminal (CT) spatial and organisational development. Symbols of development decisions as in Fig.1. Source: own elaboration.

Usually, a container terminal representing a new generation of technological solutions (CT1) is launched with a certain delay, resulting, among others, from the duration of the design and construction process of the terminal (Fig. 2). Most often, the concept of spatial development of the terminal assumes some oversizing in relation to the diagnosed needs in order to avoid the need to expand it too quickly. Based on the prognosis of terminal turnover growth, after some time of its operation, a decision A is made to expand the terminal to a specific capacity A_{max}. Usually, this decision assumes a simple continuous growth such as including the adjacent area within the terminal area. In many cases, already at the concept stage, it is assumed that the terminal will be developed in subsequent phases, so a certain land reserve for its expansion is kept.

After some time, as a result of a further increase in the terminal's turnover, another decision is made to develop the terminal (B). If it is technologically possible at a given moment, it may for example, involve increasing the storage heights in container yards (simple continuous growth). The decision to increase the reloading capacity may also involve combining several investment activities at the same time and overcoming several thresholds (A+B). Usually, as the next development opportunity, the solutions consisting of a simple discontinuous growth are considered, such as: the transfer of some terminal functions to external surfaces (C), or a change of the terminal operating system (TOS). After exceeding the C investment threshold, the terminal achieves the capacity of C_{max}, and after exceeding the D threshold, the capacity of D_{max}, or C_{max} + D_{max} in the case of the simultaneous implementation of both kinds of investments. When all the investment opportunities available under a given technology are already considered and used, both these consisting of simple growth (A, B, C, D) and in structural changes (E, F), and at the same time solutions representing the next technological generation become available (technology 2), a decision is made to build a new container terminal of the next generation (E+F). After the construction and launching of CT2 with a planned container capacity significantly exceeding the capacity of CT1, the CT1 functions parallel to CT2 for some time, but within the structure of the whole container port it becomes a secondary object.

Each investment's threshold is visible on the development curve as an inflection point. In the work of Wilmsmeier and Monios (2020), similarly as here, the inflection point refers to the moment of the port's location splitting and the initiation of the original life-cycle extension. However, we can distinguish different types of inflection points during the evolution process of container terminals and ports. The inflection points connected with the life extension of a container terminal representing one generation (development decision points) usually occur several times during the terminal's lifetime and lead simultaneously to the outsourcing of some of the terminal's activities and to the accumulation of incremental innovations within a terminal. The strategic inflection point occurs when the terminal achieves the maturity phase and is connected with a need of implementation of a disruptive innovation (building a container terminal of entirely new technological generation in a new location). Lack of this strategic investment leads to either the stagnation or obsolescence of the terminal. The strategic inflection point could be also considered through the lenses of the Thom's catastrophe theory (Thom 1975) as a moment of discontinuity in development and bifurcation of a port's possible development path (Figure 2). The change in the capacity of a container port remains continuous, but there is a complete qualitative change in the principles of its operation and spatial organisation.

The intergenerational process of container port development

The development process of container ports follows the rhythm of the emergence of the latest technologies. The concept of the cyclic behaviour of containerisation, and therefore also container ports, was extensively developed by Guerrero and Rodrigue (2014). Based on macroeconomic studies, they identified five phases (waves) of containerisation until 2010 (periods: 1956 (1965)-1975, 1970-1985, 1980-1990, 1995-2000, 2005-), illustrating in their opinion macroeconomic, technological, and also, to some extent, political shifts.

Figure 3 presents the theoretical model explaining the replacing in time of one technological generation of container port (CT1) with the next (CT2), and then the second generation (CT2) by the third (CT3) etc. The vertical axis shows the percentage share of container ports representing a given technological generation in the total number of top container ports in the world [%], describing the level of their prevalence. Following the theory of life cycles (Rogers 2003), we can assume that the number of container ports of a given technological generation firstly grows and then, after achieving domination, falls, taking the shape of the bell curve. The implementation of the first terminal of a given generation is marked on the graph slightly above 0%, which is a result of the existence of some experimental, but unsuccessful, technologies emerging all the time, as well as the process of the slow abandonment of the older generation, and the emergence of the new. Analogically, the situation of supremacy of a given container port's generation is a value slightly lower than 100%.

With reference to the product life cycle concept (Rogers 2003, Kotler et al. 2005), within each generation we can distinguish successive development stages: research and development, introduction (also called early adoption), growth, maturity and decline (Fig. 3). In analogy to the work of Solomon et al. (2000), the two following stages may be added to the previously mentioned: abandonment (also called phase out) and obsolescence, during which the process of recycling of the area of former container handling activities occurs (Figure 3). We can expect, that as the life of the previous generation is usually extended by exceeding investment thresholds and adapting to new challenges, the stage of recycling of container port facilities, understood as waterfront redevelopment process, will take place after the third-in-a-row generation is implemented.

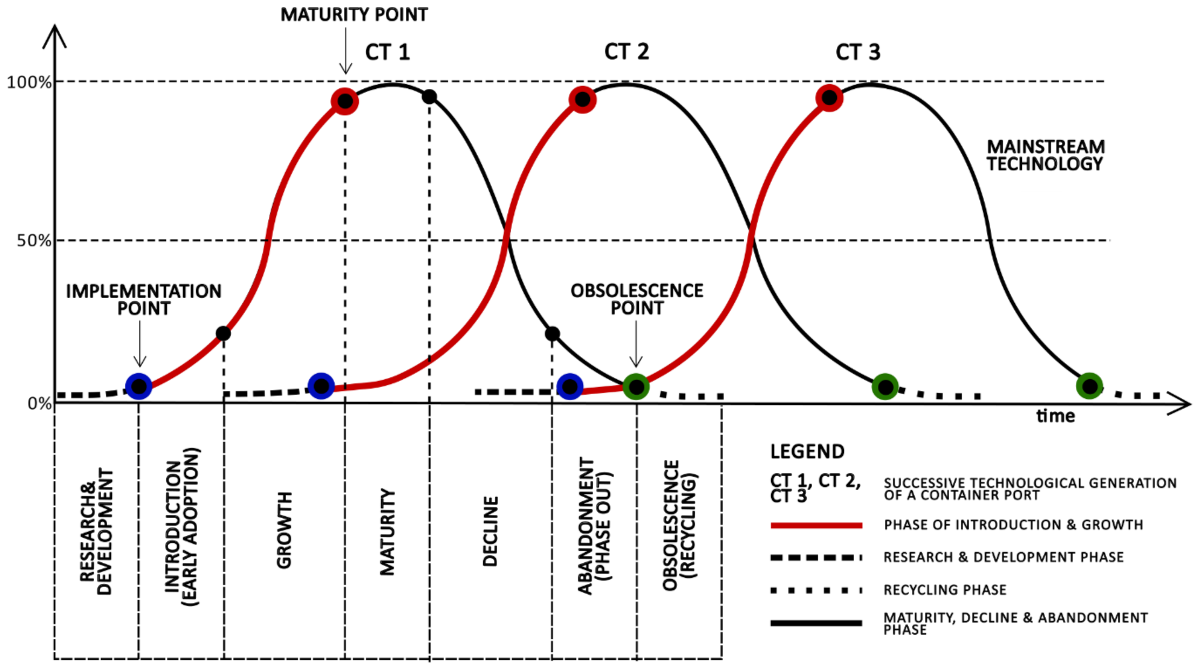


Fig.3. Theoretical model of the intergenerational process of container port development. Source: own elaboration.

It should be mentioned, that stages of research and development, and of obsolescence, are respectively: pre-stage (taking place before the first container terminal of a given technology has been even implemented – the point of implementation), and after-stage (when the last container terminal of a given technology in the world disappears – the obsolescence point). So practically, the duration of the entire generation is readable in a port's spatial development from the moment of the appearance of the first terminals of a given type, initiated by a specific technological event (implementation point) to its disappearance, understood as lack of significant importance (obsolescence point). The moment of the disappearance of a whole generation (a container port generation obsolescence point) is difficult to specify. However it is possible to define this point for a specific container port.

The maturity point, starting the maturity stage, is usually a moment of approaching the limits of rational development within a given technology. Around this time, the next generation of technology evolves, what is, to some extent, a response to investment thresholds that the existing generation has been struggling with for some time (Figure 2). While for a given generation we are able to approximate the maturity point, the strategic inflection point (Figure 2) can be determined only for a specific container terminal. However, in the case of a proper development of a container port, both these points should appear closely in time. If the next generation of container terminals is implemented soon after achieving maturity by the previous generation, the bell curve is steep and the maturity period lasts for a very short time. If it appears sometime after the inflection point occurs, the bell curve become flat at the top. So, the flattening of the bell curve during the technological maturity of a given container terminal is a result of late implementation of the next technological generation.

The period particularly visible in the evolution of container ports, as influencing the economic development, is related to their growth. Therefore, the development phases of ports and container terminals are usually analysed only in relation to the phase of introduction and growth (red line in Figure 3), while the maturity, decline, abandonment and obsolescence phases are not so intensively considered. Therefore, the concept of generation is usually shortened to the phase of its introduction and growth (period between the implementation and maturity point - compare Fig. 3).

Based on the analysis of the qualitative changes that have occurred in the technology of transporting and handling containers in ports, significant moments in the history of container handling can be identified (technological events). These events, ground-breaking and inaugurating the next technological generation indicate implementation points defined as: 1956, 1966, 1980, 1993, 2017 (Table 1).

So far, five generations of container terminals were recognised (Flynn et al. 2011, Lee and Lam 2016, Wei and Hui 2019). From a technological point of view, the first four generations were defined as: pioneer, multipurpose, specialised and automated (Krośnicka 2019). It seems that the currently emerging fifth technological generation will be based on fully automated solutions.

Tab. 1. Technological events in container terminals' process of evolution.

Dominant technology	Technological events within container terminals' evolution
Pioneer **(1956-1970)** based mostly on existing general cargo equipment	**1956 - first maritime containers in use** 1955-1964 - adaptation of general cargo terminals for container handling 1959 - the first Ship To Shore cranes (STS) are used ~ 1965 - the first Rail Mounted Gantry (RMG)
Multipurpose **(1970-1990)** based on simultaneous use of a wide variety of container handling solutions (RMG, RTG, SC, RS, semi-trailers) in one terminal	**1964 - the first container terminal, Port Elisabeth, USA** **1966 - Europe's first Container Terminal - Prinses Margriethaven in Rotterdam** ~ 1970- terminals serving only containers occurred ~ 1970 - transport and storage of containers on semi-trailers (ST) and straddle carriers (SC) ~ 1970 - straddle carriers started working in two tiers ~ 1975 - yard service by mobile cranes
Specialised **(1990-2010)** based on a one systemic solution dominating in a terminal (for example RTG or SC)	**~ 1980 - ro-ro terminals are separating spatially from container terminals** ~ 1985 - container terminals specialise and work in a uniform system (RTG or RMG or SC) ~ 1980 - gradual outsourcing of some functions to close facilities (container depot, external parking lots) after 1988- terminals are starting to be managed with the help of a Terminal Operating System (the earliest TOS was designed by Navis for APL) 1987 - new RTG generation before 1990 - only 20% of terminals in the world used computers
Automated **(2010-2030?)** based on a system of cooperating automated facilities (for example: aSTS-AGV-ASC)	after 1990 - introduction of IT management systems for container terminals (TOS) **1993 - ECT Delta Terminal in Rotterdam, the first partially automated container terminal in the world** After 1990 - construction of terminals on new lands built on water ~ 2000 - outsourcing of logistics and transport functions to close and distant facilities, including dry ports 2002 - CTA Altenwerder in Hamburg, the first terminal in Europe with aSTS technology (automated Ship to Shore cranes) 2008 - first electric RTG cranes (Terminal She Kou SCT, Shenzhen, China) 2009 - the first battery AGVs at CTA Hamburg
Fully automated? **(2030? -)** based on a unified system of fully automated container facilities	2017 - Victoria International Container Terminal (VICT), the world's first fully automated international container terminal **2017 – beginning of project YARA Birkeland of an autonomous zero-emission container feeder ship**

Own study based on: Oram (1965), Burg van den (1969, p. 134, 155), Quinn (1972, p. 554), UNCTAD (1985, 1991, 1992), PIANC (1987, p.4), Thoresen (2003, p. 312), [3], [8] , [9] , [10], [20].

Guerrero and Rodrigue (2014) noticed the strong correlation of containerisation waves with Kuznets cycles, interpreted by Korotayev and Tsirel (2010) as infrastructural investment swings lasting approximately 15-25 years. Assuming that the time period from the implementation point to the maturity point of a consecutive container terminal generation is correlated with the Kuznets cycle, and is about 20 years, the following time frames might be roughly estimated for the pioneer (1956-1970), the multipurpose (1970-1990) and the specialised (1990-2010) generations. Assuming that the nature of the container terminal development process will not change within the years ahead, it has been estimated that the generation of automated terminals (fourth generation) will reach its maturity point around 2030, and the fifth generation (fully automated) will occur in the analogical 20-year interval (2050). The occurrence of maturity points for individual generations of container ports is therefore given only approximately, but as preliminary studies show, the threshold analysis method is promising in this regard. It can be expected, that the automated terminals will gradually replace the solutions used in specialised terminals and will become the most common type of container terminals in the world around 2030. Thus, at that time, another wave of migration of container terminals in the spatial structure of ports and port cities can be expected.

In relation to the theory of Kondratiev economic cycles, Guerrero and Rodrigue (2014) expected the inflection point of the containerisation process within the fifth wave of containerisation. In relation to technological generations of container ports, such an inter-technological inflection point should be connected with an implementation of a radical innovation, related to a shift from the container technology to some other one, perhaps not based on TEU as a design module.

Case study: the development of the Gdańsk and Gdynia container ports

The ports of Gdynia and Gdańsk, although independently administered and having separate management, due to their spatial proximity – they are separated by about 20 km – share a large part of the transport access infrastructure located in the Gdańsk-Gdynia-Sopot metropolitan area. Moreover, they base on the same human capital, as well as on common transport, shipping and logistic companies operating in the metropolitan area. For this reason, the evolutionary process of the container terminals located in the ports of Gdynia and Gdańsk should be jointly considered.

Fig. 4 shows the total changes in the volume of container turnover between 1970–2020 in the ports Gdańsk and Gdynia, at the background of ports of Singapore and Rotterdam. Due to the global nature of changes in container flows, an analogy can be noticed in the occurrence of breakthrough moments in the volume of turnover on all three presented curves (the analogy was underlined by vertical lines).

The process of spatial, organisational and technological evolution of Gdynia and Gdańsk container ports is described in chronological order in Table 2 and Table 3 respectively, and on the map (Figure 5). Each of the tables include graphs presenting the investment activities in the port of Gdynia or Gdańsk in relation to previously described (Table 1) technological generations prevailing at a given moment among the top world container terminals (pioneer, multipurpose, specialised, automated and fully automated). Thus, newly built container terminals and other investments extending the life cycles of Gdynia and Gdańsk container terminals are marked on the waves of the consecutive generations. On each wave the implementation point (defined in Table 2 as a technological event starting a particular generation) and the maturity point (specified in Table 2 as the end of a generation growth phase) are marked.

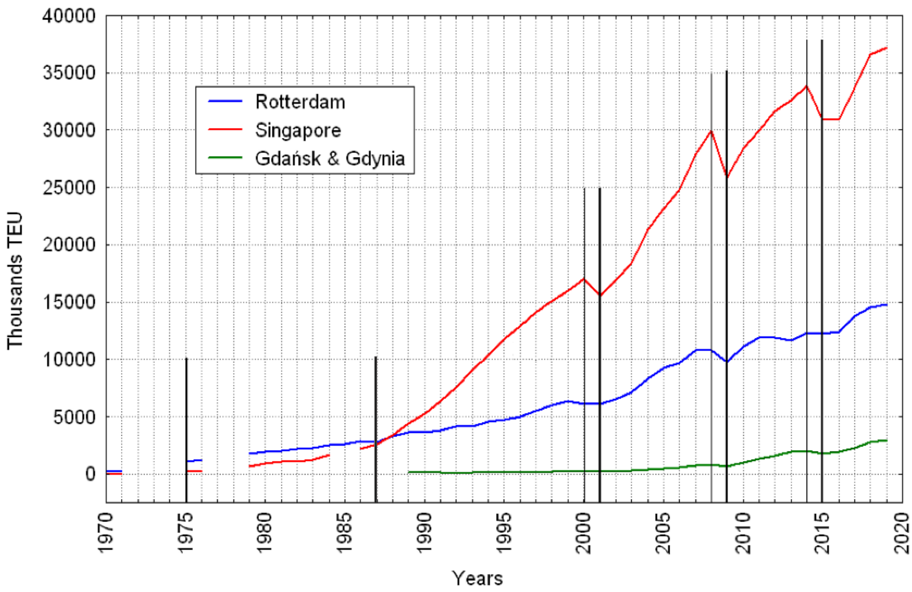
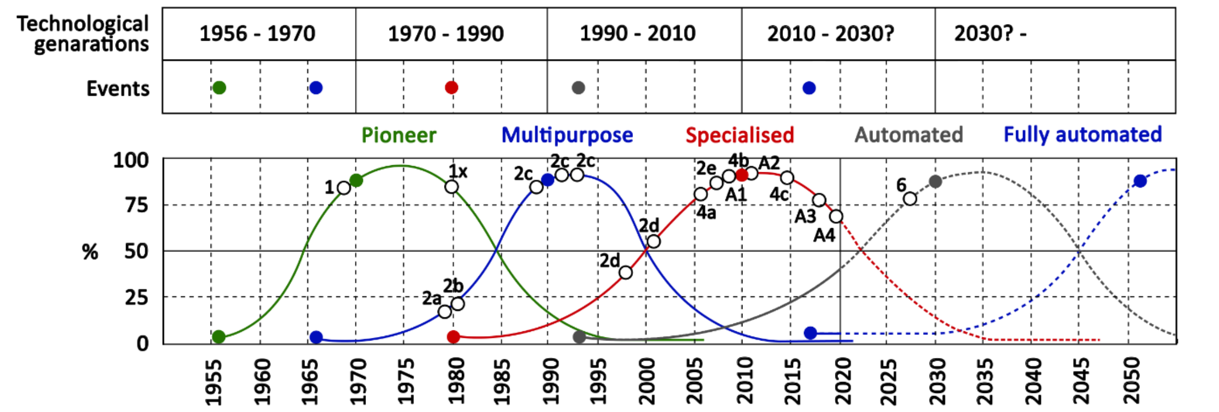


Fig. 4. Container turnover in ports of Singapore, Rotterdam, Gdańsk and Gdynia in the period 1970–2019. Source: own based on [1], [4], [5], [6], [7].

Guerrero and Rodrigue (2014, appendix), referring to the waves of containerisation, placed the container port of Gdynia in the second wave (B2) and Gdańsk in the fourth wave (D2). However, from the point of view of technological advancement of port of Gdynia and Gdańsk while erecting their first container terminals, it seems that they should rather be included respectively to the first and the third technological generations of container terminals (Table 2 and 3).

The process of developing container terminals in the ports of Gdynia and Gdańsk is fully in line with the theoretical course of the process presented in Figures 1, 2 and 3. In the case of the port of Gdynia, we can observe representatives of three (and potentially also the fourth) technological generations of container terminals, while in the port of Gdańsk there are two generations visible (and the third one is already planned).

Tab.2. Development of container port of Gdynia (Poland) between 1969-2020.



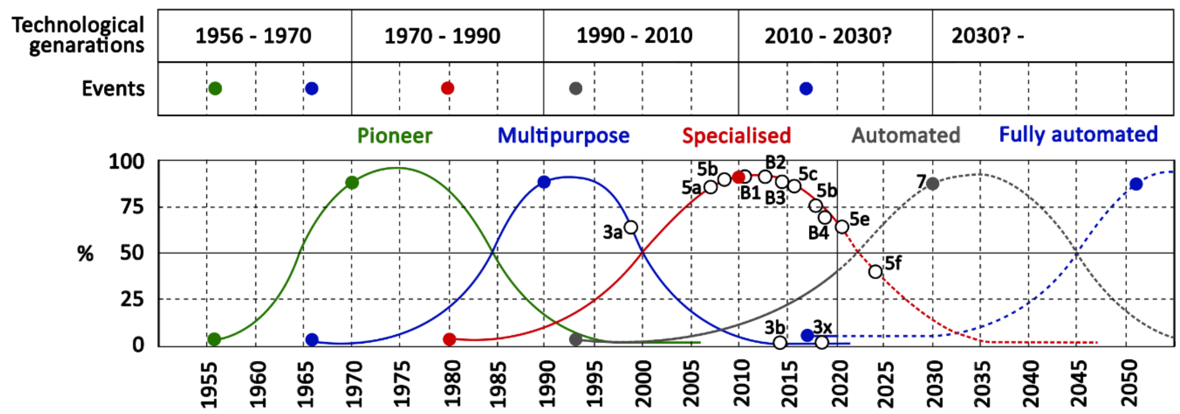
Name of a terminal	Construction year	Technological generation	No. on Fig. 5	Development Investment	Investment by Fig. 1, 2
Temporary Container Terminal in Gdynia	1969	Pioneer terminal	1.	1969 - terminal was organised in general cargo terminal at Polskie Quay as a start-up stage before launching the BCT terminal. Terminal was not meant to be further developed	0
			1X	~1980- closing the terminal	X

Baltic Container Terminal in Gdynia (BCT)	1979	Multipurpose at the beginning	2a.	1979 – launching the terminal with ro-ro service at Helskie I Quay (the first, western part of the quay)	0
			2b.	1980 – launching lo-lo service and extending the Helskie I quay towards East	A
			2c.	1989 - partial outsourcing of empty container handling to close hinterland – container depot Contex 1991 - partial outsourcing of empty container handling to close hinterland – container depots Balticon and Ref-Con Service ~ 1992 – inclusion of the neighbouring area to extend the auxiliary terminal activities	C C A
		developed to Specialised terminal	2d.	1997 – higher RTGs (switching from handling 3+1 tiers to 5+1 tiers) 2001 – excluding part of the ro-ro operations from the terminal to gain higher BCT terminal capacity (the new Ro-Ro Terminal was launched in the other part of the port of Gdynia)	B C
			2.e.	2007 – inclusion of the well-connected logistic surface in vicinity of the terminal within its structure 2007 – change of the terminal operational system (TOS)	A+D
Gdynia Container Terminal (GCT)	2006	Specialised	4.a.	2006 – GCT1 – building the new terminal	0
			4.b.	2010 – extension of the gate area	A
			4.c.	2015 – GCT2 – second phase of terminal development – extension and deepening of the Bułgarskie Quay, new STS and adjoining the new storage surface	A
Transport and logistic facilities supporting Gdynia container port	-	-	A1.	after 2006 – building in vicinity of terminals new container depot (Radunia, Produs, Ref-Con) serving both BCT and GCT	C
	-	-	A2.	~ 2010 - building several container freight stations along Hutnicza street	C
	-	-	A3.	~2015 – starting works on Gdynia Logistic Centre neighbouring with BCT and GCT (2018 – erecting the first warehouse). until 2022 - it is planned to develop new manoeuvring and storage container yards, new intermodal terminal and technological road	C
	-	-	A4.	2020 – starting works on expansion of a logistic hinterland of the port of Gdynia (so called "Logistic Valley") and building new logistic parks	C
Outer Port of Gdynia	2027?	Automated?	6.	Planned new terminal with new road access (so called Red Road)	0

Remarks: Investment type 0 – launching a terminal, type X – closing a terminal. The year of launching a terminal is defined as the year of serving the first ship. Source: own based on: Szermer (1977), [12], [14], [15], [21], [22], annual interviews with terminal employees and study visits within the years 1995-2020.

The first container operations in the port of Gdynia took place in Temporary Container Terminal in Gdynia situated at Polskie Quay (Figure 5). This terminal was planned as a start-up before launching the target terminal in 1979 - Baltic Container Terminal (BCT). The evolution process can be traced particularly well in the case of the BCT. All the investment activities mentioned in Table 2 were to increase the capacity of the BCT terminal and extend its lifespan: firstly, by expanding on neighbouring areas towards East (decision A in Figure 1 and 2), then, by outsourcing some functions outside the terminal, such as technological surfaces, container depot (C), then, while achieving the maturity point of the multipurpose technology, by inclusion additional area for auxiliary purposes (A). As further investing in multipurpose technology was not efficient anymore, the BCT decided for a structural change (F) and switching to specialised technology by an almost simultaneous increasing number of tiers (B) and excluding ro-ro operations from the terminal. However, while getting to the maturity point of specialised technology about the year 2010, the BCT decided to outsource some logistic functions from the terminal to the neighbouring well-connected area (C) and to introduce TOS, which caused a reduction of the container handling time (D) and reorganisation of the whole terminal (F). As the new specialised container terminal was created in the port of Gdynia (GCT), all further investments of the port authorities increasing the port container capacity were concentrated on supporting transport and logistic facilities in port's vicinity. Furthermore, due to land limitations within the borders of Gdynia municipality, port authorities, together with the city of Gdynia and neighbouring municipalities, have developed a so-called "Logistic Valley" project, which aims to develop transport and logistic surfaces supporting container handling within the close hinterland of the port of Gdynia. Thus, the "Logistic Valley" project, logistic parks, new container depot and freight stations, as well as new logistic centre neighbouring with BCT and GCT with its planned intermodal terminal, are an attempt to enlarge the area for auxiliary container terminals functions (C). Last years the BCT also increased the number of tiers of containers on refrigerated stacks (B). At the moment, inter alia, due to the lack of further development opportunities and possibilities of serving the largest container ships in the BCT and GCT terminals, the concept of building a new, deep-water terminal in the port of Gdynia has been developed. The planned terminal will perhaps represent an automated technological generation. With building a new deep-water container terminal, the main container handling centre will migrate from the BCT and GCT terminals to a place more favourable from an operational point of view – to the outer port. This migration process of main container facilities within the port of Gdynia is a natural necessity resulting from the logic of the evolution process and the existing spatial conditions.

Tab.3. Development of container port of Gdańsk (Poland) within the years 1998-2020.



Name of the terminal	Construction year	Technological generation	No. on Fig. 5	Development Investment	Investment by Fig. 1, 2
Gdańsk Container Terminal (GKT)	1998	Multipurpose	3.a.	1998 – terminal built as a start-up for introducing containers to the port of Gdańsk	0
			3.b.	2015 - terminal was reorganised within existing borders	F
			3. X	2019 – closing the terminal	X
Deepwater Container Terminal in Gdańsk (DCT)	2007	Specialised	5.a.	2007 – DCT 1 – launching the terminal on newly constructed pier	0
			5.b.	2009 - partial outsourcing of empty container handling to close hinterland – Balticon container depot 2010 – reorganisation of pre-gate	C+D
			5.c.	2016 – construction of a new berth (DCT2) and enlarging the terminal by an adjacent area 2017 – increasing heights of refrigerated container stacks	A+B
			5.d.	2018 – construction of the terminal 2TB – increasing rail capability and enlarging of the storage space on adjacent area	A
			5.e.	2021- adjoining 6,5 ha of land bordering with 2TB area for a new administration building, car parking and storage area	A
			5.f.	2025? – considering extension of the DCT pier Eastwards	A
Transport and logistic facilities supporting Gdańsk container port	-	-	B.1.	2010 – establishing Pomeranian Logistic Centre (PLC) bordering with the DCT terminal 2013 – construction of the first warehouse within the; PLC is still developing	C C
	-	-	B.2.	2012-2017 – building container freight stations within Gdańsk area	C
	-	-	B.3.	~2015 – building a group of container depot (Ref-Con, Balticon, Radunia)	C
	-	-	B.4.	2017-2020 – building logistic parks (Panattoni, 7R) within Gdańsk area	C

Outer Port of Gdańsk	2030?	Automated?	7.	Planned new port (“Central Port”) with a new container terminal to be developed on existing water areas.	0

Remarks: Investment type 0 – launching a terminal, type X – closing a terminal. The year of launching a terminal is defined as the year of serving the first ship. Source: own based on: [7], [16], [2] annual interviews with terminal employees and study visits within the years 1995-2020.

During the period of planned economy in the Polish People's Republic, the port of Gdańsk was supposed to serve bulk cargo, while the port of Gdynia was mainly dedicated to general cargo and containers. Therefore, the first container terminal in Gdańsk (GKT) was built relatively late, in 1998 (Table 3). The GTK was representing multipurpose technology, which was at that time already on its path to obsolescence. It was introduced as a small test terminal, which aimed to initiate the development of container operations in Gdańsk. The GKT, not being efficient and competitive enough, was closed in 2019, several years after the new container terminal (DCT) was built on an artificially landed pier in 2007. The DCT was representing by specialised technology, although at the beginning it also had a possibility for serving ro-ro cargo. The terminal was built while the specialised technology achieved its maturity. Shortly after the DCT was built, the logistic centre (PLC) and container depot occurred in the terminal’s vicinity, which was a method of outsourcing of some of terminal’s functions (decision C in Figure 1 and 2). To shorten the container handling time, the terminal’s pre-gate was reorganised (D) and the construction of a close dry port was considered (Czermański 2012). Enlarging the terminal DCT by building an additional berth (the DCT2) and the new storage space (the 2TB), were the next steps in the process of terminal growth (decisions of A-type). After increasing the area of the terminal, some external facilities supporting the work of the terminal were located in vicinity, such as container depot, freight container stations, and logistic parks (decision C). Simultaneously, the DCT increased heights of refrigerated container stacks (B). Moreover the DCT is currently considering further expansion towards East (A). Although all these investment decisions significantly increased the DCT container capacity, the port of Gdańsk authorities are currently considering building an entirely new port structure, including a new container terminal, most likely utilising automated technology (so called “Central Port”).

In the analysed Gdańsk and Gdynia container ports, the order of investment decisions follows the principle of minimising the effort - investments are usually sequenced from the simplest to the most complex. In relation to Figure 1 and 2 investments type A (terminal expansion) and C (outsourcing of some of terminal’s functions to the neighbouring areas) are the most common ones. Investments of B (increasing the stack heights) and D (reducing container handling time) types were less frequently observed. The combination of decisions used (A, C, A+B, A+C, B, F) resulted from spatial, transport, political and economic conditions existing at a given moment. In any case, the relocation process of a terminal without the change of its technological generation (E) did not take place. It is interesting, that construction of container terminals in the port of Gdańsk was taking place within the late maturity phase, while in the port of Gdynia container terminals were realised in the early growth phase or even early adoption phase (Fig. 3, Tab. 2). This is perhaps a consequence of the late introduction of container handling to the port of Gdańsk caused by political decisions. In both cases however, investment activities resulting from the need of terminal’s life extension concentrate near the maturity phase. Generally, it seems that at the moment the port of Gdynia, having no land reserves in vicinity of terminals, chooses outsourcing strategy (C) and expansion towards the sea with a new terminal, while the port of Gdańsk is basing itself on the extension strategy (A) and also considers expansion towards the sea.

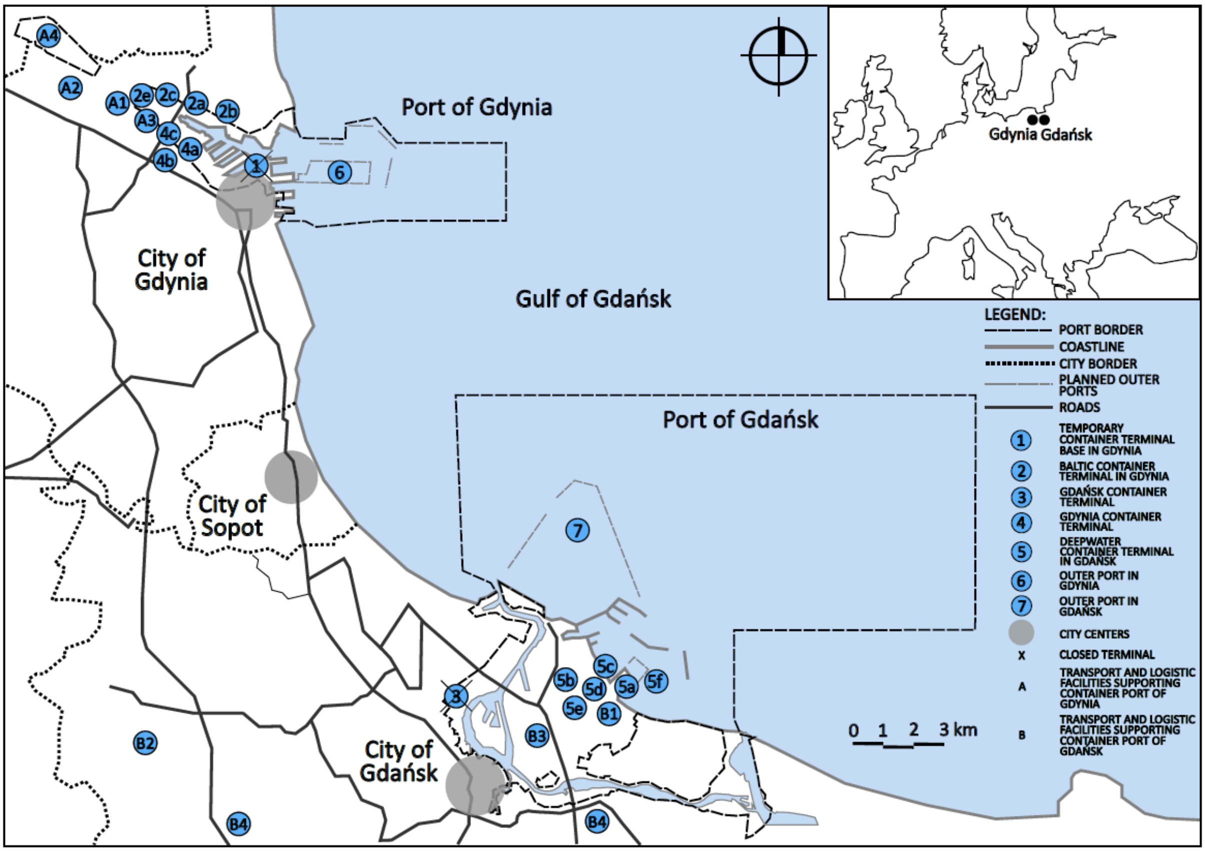


Fig. 5. Location of container terminals and their functional elements in ports of Gdańsk and Gdynia within the years 1969-2020. Source: own, based on map [11] and webpages [12], [13], [14], [15], [16], [21], [2].

Considering the physical location of development investments within the container ports of Gdańsk and Gdynia (Figure 5), it can be noticed that there are two basic directions of migration of container terminals. One is the migration of the port's main container activity (core terminal or terminals) towards deeper waters, being a result of a generational change taking place after overcoming the maturity point. The second type of migration is connected with dispersion of port development investments in the increasingly distant port hinterland, caused by the need for the life extension of terminals.

The hinterland oriented migration process of the functions outsourced from container terminals results from taking investment decisions of A type (2b, 2c, 2e, 4b, 4c in Gdynia and 5c, 5d, 5e in Gdańsk) and C type (2c, 2d, A1, A2, A3, A4 in Gdynia and 5b, B1, B2, B3, B4 in Gdańsk). The direction of migration observed in the case of Gdynia and Gdańsk ports was opposite to movement of the core container port's activity (Fig. 5).

It is worth noting that, the dispersion of functions supporting the work of container terminals in their well-connected vicinity (C) was not usually triggered by the authorities of container terminals themselves, but either by local container handling companies (container depots, some of the container freight stations in Gdańsk and Gdynia), by port authorities (in the case of Gdynia Logistic Center, Pomeranian Logistic Centre and the "Logistic Valley" project), or by land-oriented transport and logistic companies (container freight stations and logistic parks - both in Gdańsk and Gdynia).

The scheme summarising the observations on spatial outsourcing of container port functions, being a result of the A and C strategy in Gdańsk and Gdynia ports, is shown in Fig. 6.

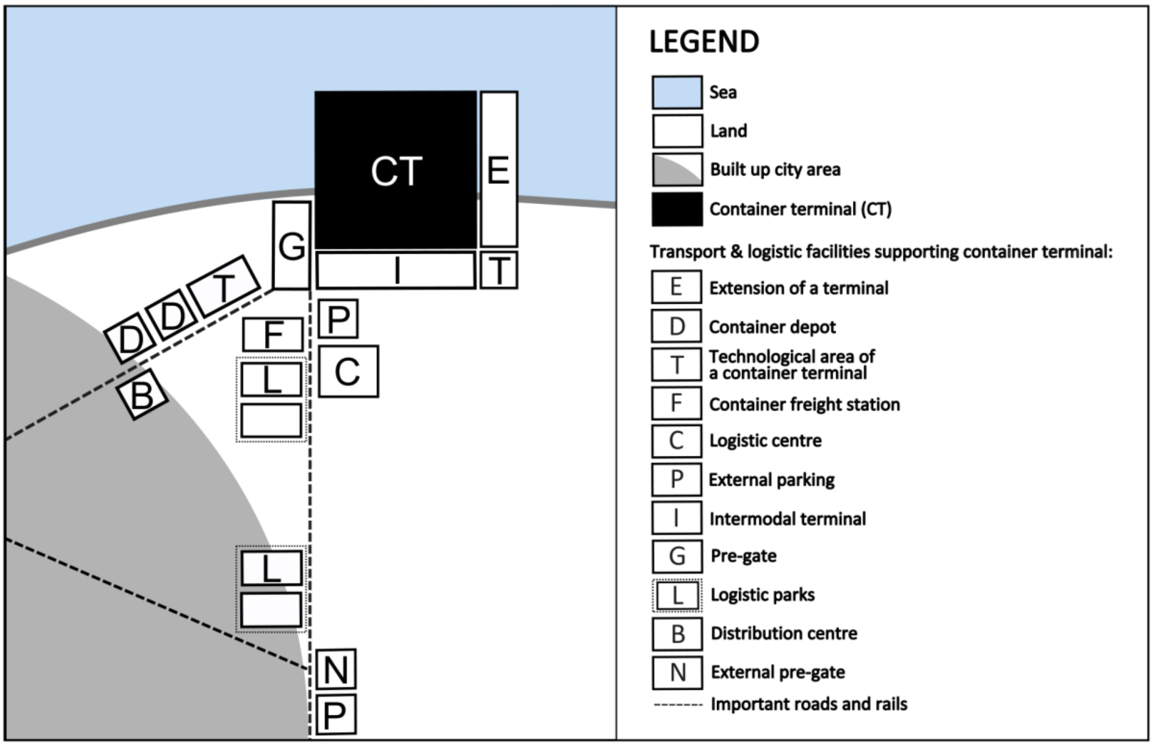


Fig. 6. Contemporary container terminal and its supporting external functions. Source: own.

Spatial migration of main container activities (core terminal along with facilities closely cooperating with it) within a port area is usually directed towards sea and foreland, which is consistent with the "Anyport" model of Bird (1971). In the case of Gdańsk, the centre of container activities moved from the multipurpose GKT to specialised DCT, from where it will probably move in the future to the so-called Central Port. In Gdynia, the gravity centre of container activities is still in the area of BCT and GCT. However it is possible, that it will soon move to the planned deep-water Outer Port. The migration process of main container activities observed in the past within the port of Gdynia, however, is much more complex. The first migration of container activities in the port of Gdynia was from the pioneer Temporary Container Terminal to the BCT, located in the inner part of the port. This migration was therefore not in line with the "down-stream" concept. However, the location of the temporary terminal was chosen as a "waiting room" before activation of the multipurpose BCT, so it can be treated as quite random.

The case of BCT is very interesting, as the full restructuring of the terminal (F) combined with A, B, C, D types of investments – in this case all types of spatial changes had occurred jointly: simple growth, discontinuous simple growth and structural change – allowed for the extension of the life of the terminal and its surroundings, and to avoid migration while shifting from multipurpose to specialised generation.

Synthesising the consideration of the development process of container ports in Gdańsk and Gdynia, and basing it on the cyclicity phenomenon of container terminal development process, a model of container terminal spatial development in the scale of port metropolitan area was proposed (Fig. 7).

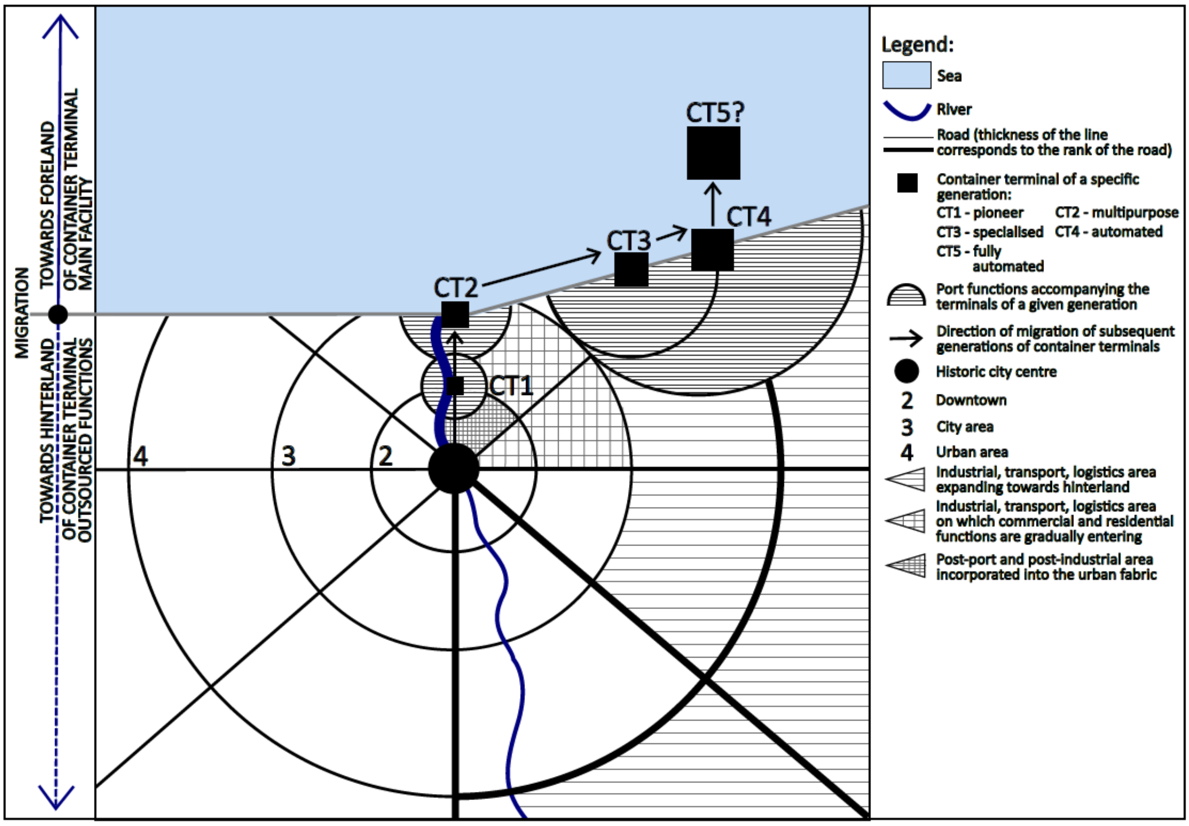


Fig. 7. Model of migration of subsequent generations of container terminals in the scale of port-city urban area. Own study, based on Krośnicka (2016, p. 66), taking into account the "Universal spatial model of port city, based on Southampton, Le Havre and Busan" (Ducruet and Lee 2006).

With a generational shift the main container activities (terminals of each generation: CT1, CT2, CT3, CT4, CT5) migrate towards the sea. Along with the core terminals, their accompanying functions also migrate (such as intermodal terminals, external parking areas, pre-gates and logistic centres). The surface of each following generation of terminals and their supporting facilities is significantly larger and the access infrastructure both from water and land is improved. This usually causes a decrease of the importance of terminals of the previous generation and their gradual decline. When the next generation of container ports is fully developed and the newer generation is occurring, the terminals of the previous and their supporting facility generation undergo a process of abandonment and finally recycling. This process manifests itself in the gradual entering of other transport and commercial functions into this area. At the same time, with each of the container port generations occurring, the logistic and transport functions outsourced from core container terminals have an increasing area and are increasingly technologically advanced and dispersed over the port's metropolitan area and its close hinterland.

Conclusions

The paper proposed a theoretical model explaining the mechanism of container terminal spatial evolution within the area of a port and indicated moments of their potential spatial migration of a various type. The model was built on the basis of existing theories concerning both generational and intergenerational changes. The life cycle theory (Rogers 2003, Kotler et al 2005, Liefner and Schätzl 2017, Solomon et al 2000), the threshold theory (Kozłowski and Hughes 1967, Malisz 1970) and the Kuznets' swings (Korotayev and Tsirel 2010) have been used to describe the development process of a container terminal within one technological generation. While the life cycle theory, the threshold theory and the theory of Kondratiev waves theory (Korotayev and Tsirel, 2010) helped to explain spatial changes taking place within container ports during the whole process of containerisation. The catastrophe theory (Thom 1975) was proposed in both cases to explain the discontinuous changes within the process. Thus, the model tries to combine and interrelate both – mostly separately considered in the literature – approaches towards container terminal evolution: a life cycle of a terminal within a single technological generation (Monios and Bergqvist 2017, Wilmsmeier and Monios 2020), and a life cycle of the whole containerisation process within a port (Notteboom and Rodrigue 2009, Guerrero and Rodrigue 2014, Lee and Lam 2016, Wei and Hui 2019). The model, however, is based mainly on the technological aspects of the spatial and organisational development of container terminals.

The model assumes that the life cycle curve of a single generation of technological container terminals has a shape similar to the bell curve, and that it consists of the following development stages: research and development, introduction, growth, maturity, decline, abandonment and obsolescence. Based on analogies to the work of Solomon et al. (2000), the model developed an understanding of the decline stage. It did this by distinguishing within the previously-described stages of a container terminal life cycle (Monios and Bergqvist 2017, Wilmsmeier and Monios 2020), the stage of abandonment (phase out) and the obsolescence stage, during which the process of recycling occurs within the area of a former container terminal. The course of the life cycle of the containerization process is, in turn, understood as the overlapping successive bell curves, representing individual generations of container terminals, the maturity points of which are shifted relative to each other by about 15-25 years. This shift is correlated with the duration of infrastructural investment swings of Kuznets (Korotayev and Tsirel, 2010). As the course of the growth period of a particular container terminal generation – understood as a period lasting from implementation of a given generation until gaining maturity – takes the form of an S-curve, the course of the entire container port development process is the sum of the successive S-curves (compare Jeevan et al. 2020). As a result, the concept of generation is usually only perceived through the lenses of growth periods from subsequent generations, without considering periods of their decline. For example, within the life cycle of the containerisation process, Guerrero and Rodrigue (2014) noticed five phases (waves) of containerisation up until the year 2010: 1956/1965-1975, 1970-1985, 1980-1990, 1995-2000, 2005-. In the model, the life span of subsequent technological generations of container terminals were estimated as: 1956-2005 (pioneer generation), 1965-2020 (multipurpose generation), 1980-2045? (specialised generation), 1993- 2065? (automated generation), 2017-? (fully automated generation). However, the growth phases of the following generations defined by the model are: 1956-1970, 1970-1990, 1990-2010, 2010-2030, 2030-2050. They correspond with the phases suggested by Guerrero and Rodrigue (2014), provided that we treat phases 2 and 3, as well as phases 4 and 5, as combined.

According to the model, upon achieving the maturity stage, a container terminal of a given generation reaches the strategic inflection point on the bell curve, and then the implementation of a disruptive innovation occurs - a new container terminal of the next technological generation is built within the port area. The erection of a new container terminal, usually further from urbanized areas and in deeper bodies of water (compare Fig. 7), is perceived – from the perspective of the last 65 years of containerisation – as the migration of container terminals towards the sea and foreland, which is consistent with the "Anyport" model of Bird (1971). Currently, the first cases of the fifth generation of fully automated container terminals have emerged. However, in most of the ports the specialised generation of container terminals still dominate, and the number of ports with automated terminals is increasing. We can therefore assume, that the automated terminals will gradually replace the solutions used in specialised terminals and will become the most common type of container terminals in the world around 2030. Thus, during this time, another wave of migration of container terminals in the spatial structure of ports and port cities can be expected. According to the model, the recycling of a container terminal of a given generation (waterfront redevelopment process) takes place after the implementation of the third-in-a-row generations of container terminals. The model explains therefore, why the new container terminals emerge within the port's structure, whilst the old ones disappear, confirming Merk's observations (2018).

Similarly as Cullinane and Wilmsmeier (2011) state, the model treats development of a container terminal of a given generation as a continuous, cumulative process of implementing incremental innovations, which in turn are reflected in spatial and organisational changes within the container terminal itself and within a port. Following the approach of Cullinane and Wilmsmeier (2011) in terms of the need to distinguish between the process of "growth" and "structural change" while considering spatial development of a container terminal, the model defines types of possible implemented changes (understood as investments) and describes the order of their occurrence. This is consistent with the Zipf's (2012) principle of "the least effort", by using a semi block-diagram. The considered investments however refer only to the strategies of physical and operational restructuring of container terminals, as they influence the spatial structure of a container terminal. The strategies of the container terminal life extension based on the institutional investments, proposed by Wilmsmeier and Monios (2020) as the third possible option, are not taken into account here. Thus, according to the model, the implementation of investments under ideal conditions starts with simple continuous growth (A- joining the new development area to a terminal, B – increasing number of tiers on a container yard). It also goes through complex growth (C – outsourcing some of the terminal's function onto surrounding areas, D – reducing the container handling time). It then ends with the investments demanding the structural change of a terminal (E – relocation of the terminal, F – implementation of the new generation's technological system within a terminal). Each of these investments, visible as the inflection point on the bell curve, is connected with overcoming the development threshold and extending the life of a terminal. In the work of Wilmsmeier and Monios (2020), similarly as here, these inflection points refer to the moments of the terminal's location splitting and the initiation of migration of certain terminal activities towards either close or distant hinterland (container depots, container freight stations, external car parks, dry ports etc.).

The analysed evolution process of the ports of Gdynia and Gdańsk conforms with the proposed theoretical model. Container ports and terminals in Gdańsk and Gdynia develop in two ways: through continuous or discontinuous growth, and through structural change (erection of new generation container terminal or terminals). This results in two types of container terminal migrations within the Gdańsk-Gdynia-Sopot metropolitan area: the migration towards the sea of the core part of container activities (with one exception of a temporary terminal built in 1969), and migration of external facilities cooperating with a terminal towards the close hinterland, particularly along main transportation axes. This proves, that the migration of container terminals within these ports is a part of their natural process of evolution, being a consequence of their threshold development and location splitting.

In the analysed case study, the order of investments occurring in terminals was usually sequenced from the simplest (simple growth and discontinuous simple growth) to the most complex ones (structural change). However, the investments type A and C, connected with spatial growth, were more common than B and D - related to terminal reorganisation. No relocation process (E) was observed. However, an interesting case of deep reconstruction process (F) of the BCT terminal was noted, which allowed the terminal to extend its life for the whole next generation (it shifted from multipurpose to specialised generation). This was probably possible due to using a short-lasting innovation window, when the potential development paths of the terminal were still not too far from each other.

The case study of both the Gdańsk and Gdynia container ports proved that the dispersion of functions supporting the work of container terminals in their well-connected vicinity was not usually triggered by the authorities of container terminals themselves. It was found to be triggered by local container handling companies, port authorities, or land-oriented transport and logistic companies.

The case study of the Gdańsk and Gdynia container ports give rise to supposing the idea that the proposed container port development model is correct. However, it requires checking on further examples and tracing the spatial and organisational evolution of many other container ports and terminals.

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