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Spatial Development of Modern Port Structure and Sustainable Urban Growth within Multifunctional Organization

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ABSTRACT: Modern port city areas face enormous opportunities due to their coastal location. The possibility of integrating water area into a city area highlights the issue of spatial planning. It is obvious that such locations allow for the development of industrial and port infrastructure. But the major question is how these areas should develop in terms of architecture and urban planning. The aim of the paper is to define the design parameters for maritime areas in the context of the modern city, as well as with regard to sustainable development of these structures. The analysis of modern port centres allows for indicating the directions of development in the pursuit of expansion into water areas. The scale of modern commercial and industrial structure may become dominant, and sometimes even limit the multidirectional development of the city. However, the key issue is how to design these areas in the future, also in relation to the social perspective.

1 INTRODUCTION

The definition of a modern port city has evolved. With the growing demand for the distribution of goods for individuals, corporations and industries, the logistics structures of ports try to meet those. The increased presence of components in the management, maintenance, construction and operation systems affects the future directions of port development [1]. Modern approaches show that optimization and modernization of only some elements of the structure, for example the automation of the cargo handling process in seaports, may create more functional, performance-oriented, effective and safe solutions [2].

In the functional core of a port city, we can find multiple types of different building structures that are placed in defined location zones. The relationships between these areas of influence are often closed. Their functioning also requires monitoring and assessment of dynamic units that use the infrastructure, the impact of which should also be considered in terms of use in sea-land connections [3]. The implementation of port structures automation in all areas is increasing year by year. In order to address this major challenge, coordinated actions are needed to define a global system based on the autonomy of systems [4]. This refers to the aspect of optimizing complex technical systems.

Port cities, as the name defines, apart from their industrial and service character, are places to live. Land management policies depend on numerous factors [5], where the control and implementation of land use are regulated by an increasingly complex and bureaucratic system of adaptive planning.

As investigations in coastal cities show, the port system and the city system are interconnected [6]. Due to the organizational plan of the port city, management may result in a decrease of efficiency, although in some cases an increase of prosperity of the urban agglomeration is visible. From a global perspective point of view, the urban environment strives for development in all areas.

A comprehensive approach to the sustainable development of the port-city complex areas should be defined by the perspective of multiple port stakeholders [7], as well as the social, economic and political structure of the city [8]. Relying on the direction of the main policy to limit the external growth of the agglomeration and at the same time maintain economic growth involves many dependencies between the entities creating the entire structure. Furthermore, such a synergistic relationship should be directed in all ways towards the defined fundamental criteria, including aesthetics, functionality, environmental protection, system security, system efficiency and functional flexibility [9]. The highest correlated values create the idea of environmental sustainability. Therefore, building a design structure of a given region should include these basics and also lead to detailed definition of other elements at lower levels that would be applicable to the above.

2 RESEARCH METHOD

The form presented in this paper is defined by fundamental research based on a literature review and an analytical approach to the problem. The definition of this work outcome is the sum of conceptual research, in which many interconnected elements provide a complete overview of the problem scale. Defining the elements of spatial development, such as the functional structure of the city and the functional structure of the seaport, it is possible to present the current state of knowledge. Analysis of existing structures of port cities allows defining key features regarding the functional impact of the port on the city system. Moreover, defining growth trends allows us to assess which problems can be solved at the conceptual design stage of such facilities. Consequently, in order to counteract undesirable and destructive effects, an appropriate organizational model is defined.

Figure 1. Diagram of the impact of the port structure on the environment [by M. Gerigk, 2025].

The inclusion of the main elements of the environment system is crucial to properly position the role of the port and to show the directions of influence that create relationships between these elements. As shown in Figure 1, the port is a central element of the natural environment, maritime area and city structure, where the overlapping sets are characterized by their basic motives of existence in order to create equilibrium. Therefore, the main question is how the port can be formed to maintain the most neutral influence towards its surroundings, referring to environmental protection, efficient distribution of transport and social approach to urban management.

3 SPATIAL DEVELOPMENT OF WATER AREAS

3.1 *Functional structure of the city*

Urban structure is defined by numerous elements. Over the years, urban form developed in various ways. The way it is shaped is related to the dynamics of its development depended on many factors, including defence, trade, strategic planning, manufacturing, etc. However, nowadays, thanks to advanced forms of spatial planning, it is possible to manage the city in a very precise way, and this can be done regardless of location. The significance of a city is based on its size and composition. In the case of small cities, the increase in size may cause the acquisition of regional importance, while large cities may gain significance through the growth of regional and international network connections [10]. The composition of a city depends on the placement of its inner elements, as well as on the structure of its geographical location. The analysis of the relationships between the elements of a city can be done with a spatial representation. For example, comparing sketches of road, water and tram transport can be a point of reference for creating a graph [11] that allows for evaluating the performance of connections in a defined network.

The structure of the city's land management is defined by land-use categories [12]. Figure 2 presents a diagram of urban land-use categories, where the city structure concentrates them and coordinates the relationships between categories. The main categories of functional land types are as follows: multifamily and residential, public utility, retail and commercial, industrial, institutional and public, recreational, natural environment, transportation, and seaport.

Figure 2. Diagram of the functional structure of the city [by M. Gerigk, 2025].

3.2 *Functional structure of the seaport*

Port cities are a reflection of the sectors of the economy, in which the impact of intensive growth in modern days can be observed. The distribution of goods is related to the nearby urban structures of the port, where the operating logistic system transfers goods to in-place end users or to external logistics distribution centres. The supply chain around large urban centres relies on various means of transport and various building structures. As a specified element of the city in the form of an urban land designated for a port, it should be characterized by the way it operates as a local main distribution centre, where the functioning of which is optimized for the distribution of goods and services. Moreover, the operation of such a facility depends on the arrangement of buildings and technical devices in a given location. Their efficiency of connections is based on the organization of transport, which allows the delivery of goods towards land routes or vice versa to overseas destinations.

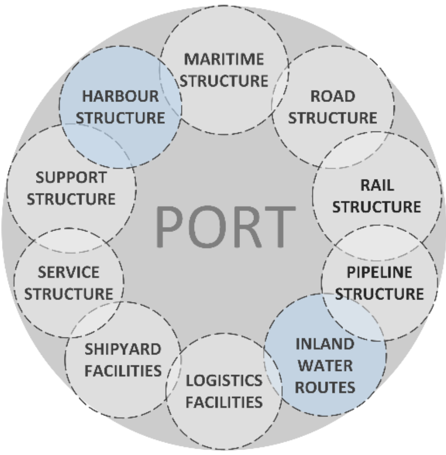


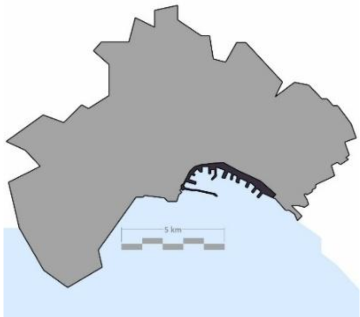
Figure 3. Diagram of the functional structure of the port [by M. Gerigk, 2025].

Within the development of port areas, the following types of structures, presented in Figure 3, can be distinguished: harbour form, maritime transportation, road transportation, rail transportation, pipeline transportation, inland water transportation, logistics facilities, shipyard facilities, complementary service and support. Maritime, road and rail facilities include the means of transport associated with them. Considering design issues, it would be necessary to determine the framework limiting the overall structure. This would be of key importance for the organization of urban shoreline.

3.3 *Location and conditions of economic geography*

There is a tendency to build more land-water structures as a consequence of spatial constraints of a given city location. Such activities concern many stakeholders [13]. The basic conditions of a port city depend on the geographical and natural structure, and then on the overall investment outcome, i.e., the entire built environment with infrastructure, and finally on the intensification of human operational activities. The development of a given port centre is determined by many factors, for example the historical factor, where the development of infrastructure for many years depended on territorial ownership and the intensification of activities, whether service or economic. The emplacement of a port in the existing city structure can show important features that define the way this structure works. The schemes below present several examples of the city structures in light grey and the locations of ports in dark grey.

a)

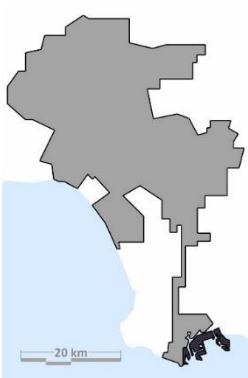


b)

c)

Figure 4. Port infrastructures: a) in Gdynia, Poland, b) in Naples, Italy, c) in Singapore [by M. Gerigk, 2025].

As shown in Figure 4, the location of the port relative to the city can be diverse. In Figure 4. a) the inland location of port is shown. The advantages of such a location are that the waterline of the city is larger than the port structure. This affects the entire industrial zone, which must be organized in a concentrated manner. The reverse solution is presented in Figure 4. b) where a port composition is parallel to the waterline, which limits access to the sea. When analysing examples of the organization of port structures, it is worth choosing cities that are characterized by the ongoing development in size. In Figure 4. c), the port structure of Singapore is configured so that it covers half of the area on the ocean side. In addition, industrial structures reach out to the outer islands, which create an exceptionally large area of influence in the region with extensive industrial and production facilities.



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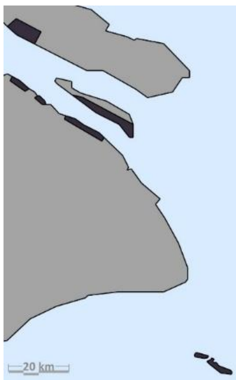

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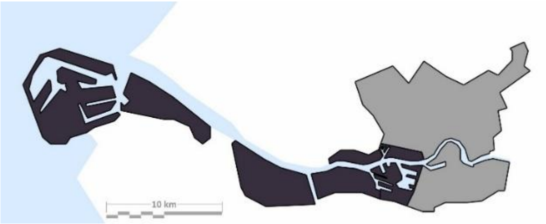


c)

Figure 5. a) Port infrastructure in Los Angeles, USA, b) Port infrastructure in Shanghai, China, c) Port infrastructure in Rotterdam, Netherlands [by M. Gerigk, 2025].

Analysis of examples allows to visualize different configurations of port locations in relation to the main urban centre. The Los Angeles City agglomeration, presented in figure 5. a), relies on a sea distribution located at a considerable distance from the main city structure, despite the potential coastline located much closer. Such a composition results in avoiding unnecessary transport communication within the urban centre, but the overall structure is typical, as it contains elements of the mainland and an extension towards the sea.

Shanghai, shown in Figure 5. b), as the world's biggest port, has one of the largest port services areas. Regarding the scale, these objects may slightly separate the city from the water. It is worth emphasizing the location of two island of the container terminal in the southeast of the city, several dozen kilometres away, which are connected by a bridge. This solution completely eliminates the impact of water transport on the urban centre because the only connection is road transport between lands.

The port of Rotterdam, which is the largest port in Europe, has an interesting form of evolution presented in Figure 5. c). The former port located in the very centre of the city is situated in the river delta at some distance from the ocean. However, with the progress of development, it turned out to be insufficient and began to cover larger and larger areas along the delta. At the current stage of development, a platform on the water was created in the form of an artificial island, which significantly increased the port's capacity due to its size. In addition, easy access to sea transport and distribution routes results from the peripherality in relation to the city.

Figure 6. Port infrastructure in Tokyo Bay, Japan [by M. Gerigk, 2025].

Figure 6. presents part of Tokyo Bay. This example shows the layout of the port in Tokyo with several interconnected urban centres around, which have an extensive port infrastructure. The linear development and the connection of many agglomerations resulted in the significantly limited access to water areas from urban areas. This effect is eliminated by building a large number of artificial islands for industrial and urban purposes. The formation of a buffer layer between the land and water areas, as well as the reduction of the bay area is clearly noticeable. However, with such a large form of industrialized area, there is an elevated risk of environmental pollution.

3.4 *Spatial development of water areas*

Water areas can be incorporated as an integral part of the city. Considering the possibilities of expansion on water, it is greatly beneficial for the urban centre. Figure 7. presents the current map of Gdańsk. The administrative boundaries of the city previously included only the land structure. What is new is that this area now also includes water areas. The area covered by the city has doubled. For the developing transshipment centre, this is a motivation for better management and expansion of the existing port structure.

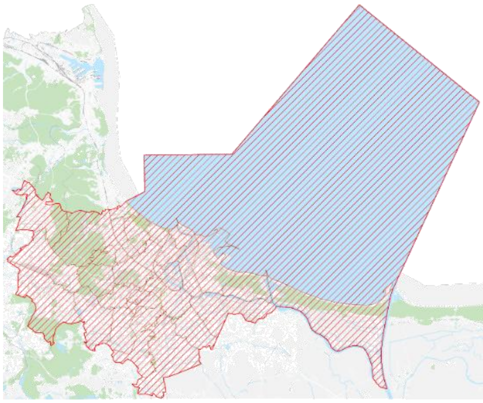


Figure 7. Administrative boundaries of the city of Gdańsk, Poland [14].

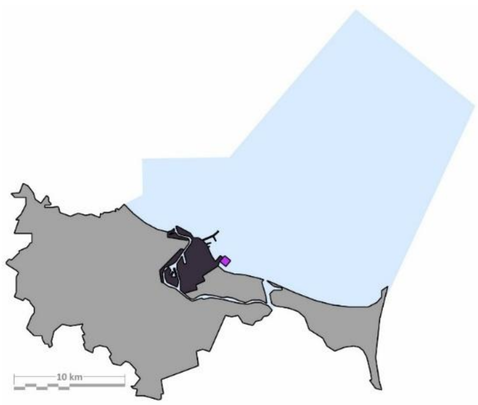


Figure 8. Port infrastructure in Gdańsk, Poland [by M. Gerigk, 2025].

The Gdańsk agglomeration is spreading asymmetrically. In Figure 8, the shape of the city is marked in light grey. The port area in dark grey is located in the central part of the coastline of the city. The port structure is well-developed and arranged in a compact manner. The port infrastructure reaches all the way to the city centre, which creates extremely favourable conditions for creating a local distribution centre. At the same time, container transport has a favourable road and rail connection, which bypasses most of the city area. In recent years, there has been a significant evolution of investments in the logistics support structures and the container terminal [15]. In order not to interfere with recreational areas, the new terminal was located at a distance from the beach. In Figure 8, the square shape in purple shows the next stage of expansion of the container terminal, which is currently under construction. This investment will increase the cargo handling capacity by half. Regional market conditions of the offshore industry conformation suggests that if the port infrastructure is to be efficient, it should also be organized with reference to the entire urban structure.

4 REORGANIZATION OF THE FUNCTIONAL STRUCTURE

As a consequence of the spatial constraints of a given city location, there is a tendency to build more land and water port structures. However, the provision of this expansion should be limited by the functional and spatial values of the city. Exposure to water should be ensured for other functions, especially for recreational and natural areas. Figure 9 presents a diagram of the port extension area. The port area should occupy the smallest possible urban space and the city should have access to a free water area, from which only the water transport lane is separated. The connection between the port and the city should be ensured by multifunctional structures, as this facility should provide support for all land movements. The compactness of the entire solution would depend on this. Moreover, the land communication route should reach the city borders as quickly as possible.

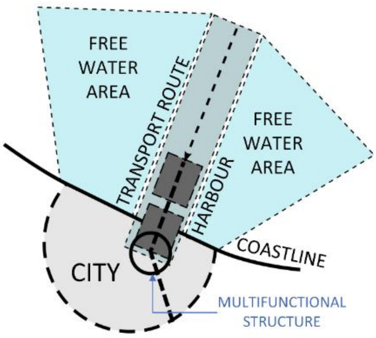
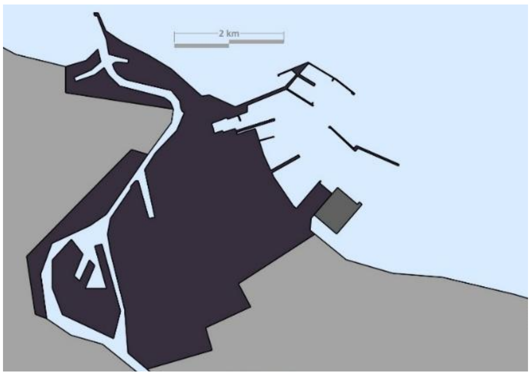


Figure 9. Diagram of the port expansion area [by M. Gerigk, 2025].



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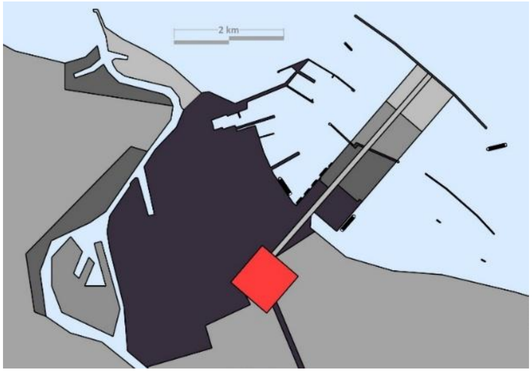

b)

Figure 10. a) The area of the port of Gdańsk with current structures, b) Scheme of the reorganization of the area of the port of Gdańsk [by M. Gerigk, 2025].

The proposed development structure is presented using the example of the city of Gdańsk. Figure 10. a) shows the current state of the port area. In a short distance from this area, towards the city centre, multi-family and public utility buildings are being built. This dynamic development would shift industrial and seaport structures due to land prices. Hence the need for new building structures, the new configuration, unlike the previous one, can be prepared for modern type of structures and standards. The construction of the external port is shown in Figure 10. b). The gradation of grey colours shows the stages of development into the water area. At the same time, it shows the withdrawal of industrial facilities from urban areas, enabling revitalisation. The new port structure is connected by a multimodal transport route with the multifunctional facility (marked in red on the scheme).

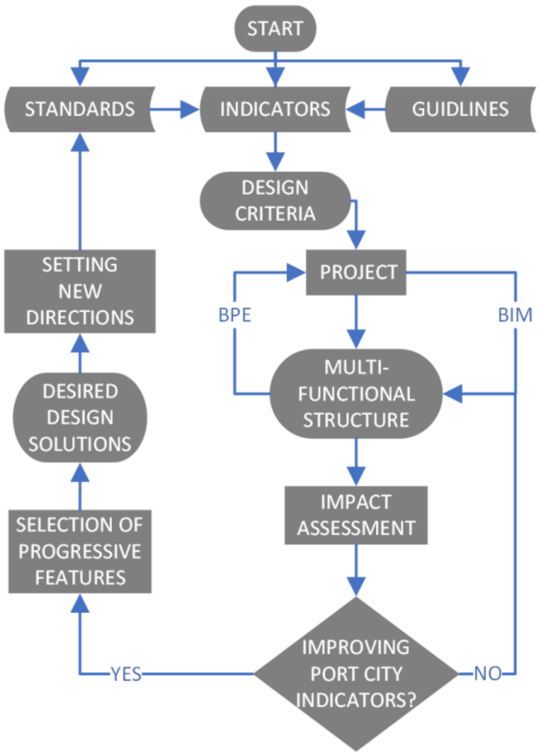

Figure 11. Flow chart of the genetic algorithm focused on consolidating the process of designing a multifunctional structure to improve the port city [by M. Gerigk, 2025].

The main goal of this new structure is to improve the performance of the port and at the same time make the city a better place to live. Considering modern technologies, this system can be created as a reconfigurable structure. Figure 11 presents a genetic algorithm focused on consolidating the process of designing a multifunctional port structure. The improvement of the structure is possible by controlling the built elements of the system and assessing their influence on the system's performance. Each completed project would be defined by a Building Information Modelling workflow and measured by Building Performance Evaluation. This type of process management is also directed towards improving standards.

5 CONCLUSIONS

The presented results show the solution of the problem of modernization of the city port structure from an architectural point of view. Different scenarios of development of modern port structures indicate that their expansion is mainly directed towards water areas. This development brings negative effects to the environment and to the people living in these cities. The extensive growth of port structures and occupying an increasingly longer coastline can bring urban chaos and naturally increased pollution. The expansion of a container terminal in one direction could save the coastline for the benefit of urban centres. This type of extensive construction is implied in many ports, but their growth is organic rather than controlled. It is important to define the crucial elements of the system to create a modern multimodal centre. Moreover, the proposed design approach defines the connection of the main port structure with the land. The considerations in the paper include importance of transforming the container terminal into a multi-level logistics centre. The paper comprehensively defines the most important systemic design elements related to the development of water city areas for the coexistence of industrial, logistics, residential and public utility structures. Further considerations should include the improvement of logistics operations in the local structures by providing autonomous means of local transport. The presented design structure could be a system with automated transfer of diverse types of goods. Water areas can satisfy potential growth of a city. Port facilities should be designed in a compact and optimized manner. There is a vast diversity of port shapes around the world, and perhaps standardization in the design of such structures could benefit the management of traditional and autonomous fleets.

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