Maritime Transformable Area Systems:

Towards Sustainability in Factory Planning and Development

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ABSTRACT

Transformable area systems (TASs) offer new possibilities for sustainable factory planning and development, notably as regards maritime structures. This is of relevance to factories of the future and could constitute a major influence in future factory planning and operation (i.e., the way in which factories are planned, implemented, transformed, relocated, used, and managed). Floating pontoon islands with solar systems already exist, and so much more is possible with similar but more complex structures. This article explains the basics of the TAS concept, assesses its potential, and discusses the future possibilities. It concludes that lack of knowledge and awareness about TASs and their potential is holding back their application in practice. Omnipresent short-term thinking and short-term profit expectations are further hurdles that are limiting the further development of TASs at present. TASs could nevertheless contribute to the improved functioning, sustainability, and future viability of factories, other structures, and their development.

KEYWORDS

Circular Economy, Factory of the Future, Fourth Industrial Revolution, Sustainability, Sustainable Development, TAS

INTRODUCTION

We live in a dynamic world, but use static and immobile physical structures, with many consequent disadvantages. The core problem is that terrestrial areas are non-transformable. This is especially relevant in the case of factory transformations, leading to cost-intensive and time-consuming demolitions, reconstructions and new constructions, which make existing factories antiquarian, as they are neither sustainable nor efficient. One way forward is to build transformable structures, located at sea in marine environments or other water bodies. For these structures, the term Transformable Area Systems (TASs) is used. Diverse TAS-like developments, such as floating solar systems, exist (ABB 2017, 2019) and the growing concerns for the environment (Rueff, 2020) are bringing the feasibility of using TASs more into view, as does Oxagon, the “world’s largest floating structure” (Neom, 2023). The main objective of this article is to introduce and discuss the TAS concept and its potential, for which Scanlan (1974), Hernández (2002) and (Sredić, 2018) are notable sources.

DOI: 10.4018/IJAIE.330969

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The non-transformability of terrestrial areas is the underlying problem that leads to diverse negative factory developments and characteristics throughout factory lifecycles, and this is scarcely recognised in factory planning theory and practice. It is important to recognise the significance of area transformability facilitated by TASs. A TAS needs to be modular, mobile, pluggable and scalable, provide additional spaces, and have at least one functional layer for substructures – for example for the housing of supply and disposal infrastructure. Compared to terrestrial areas and terrestrial area-based factory structures, TASs can achieve a significantly increased area, substructure and superstructure transformability. The TAS concept is not only a potential opportunity for factory development, but also for many different structures and uses, and their combination.

Following this introduction, the literature review explores relevant sources from several disciplines and fields of knowledge. Then, the research methodology is discussed, which is mainly based on an integrative literature review and the analysis of real-world factory developments. As part of the findings from this research, the basic concepts and features of TASs are outlined, and the current potential and issues for the future are discussed, building upon the views of different authors of relevance. Finally, the conclusion pulls together the main themes of the article, looks at possible areas for future research, and provides an outlook to a possible future.

RELEVANT LITERATURE

Non-recognition of the transformable area concept: Even though flexibility, transformability and modular factories are discussed in factory planning literature (Wirth, 2000; Schenk et al., 2014; Wiendahl et al.,2015; Grundig, 2018), most of the factory theories, models and concepts do not consider transformability requirements: the problem of non-transformable areas and their impact is generally not recognised. Similarly, the recent literature on industrial engineering, Industry 4.0, and the "factory of the future" (including the "smart factory") does not adequately consider factory developments and lifecycles. The active transformability of areas and the necessity that factories should have this capability are not considered.

Factories that are constructed upon terrestrial areas are restricted and currently barely transformable. Numerous demolitions, reconstructions, new constructions, and thus continuous destruction of usable structures and tremendous waste of resources are consequences. Furthermore, most factories and production networks are inefficient for the large part of their lifecycle, while the use of synergies is very limited. The loss in efficiency of today's automotive manufacturing plants throughout their lifecycle through remodelling, suboptimal operation and complex management is high. Such factories and production networks are unsustainable, and environmental destruction occurs as a consequence. The transformability and transformation velocity of today's factories are low and decrease throughout their lifecycle, while complexity increases. Numerous transformation requirements occur and increase throughout factory lifecycles, but the possibilities of meeting these requirements are limited, and decrease (Sredić, 2018).

The impact of non-transformable areas: Existing literature concerning factories of the future discusses a range of themes, including "adaptive and smart manufacturing systems", "highly competitive distributed manufacturing (flexible, responsive, high speed of change)", "lowest resource consumption energy – lean, clean, green", and "sustainability in material, production processes/ workers" (EFFRA, 2013, pp. 28–29). These aspirations do not match the reality of today's factories and will be difficult to achieve with terrestrial area-based factories alone. Figure 1, for example, depicts a construction site in the city of Karlsruhe, Germany. Such structures are anything but transformable, and diverse requirements and negative effects occur, for example, on traffic. The question is not only "what should be done and how?", but rather "what could be done, and how if transformability is to be achieved at a new level?".

The significance of transformable areas: Factories need to be viewed as living organisms, allowing them to change their position, be extended, exchanged or otherwise transformed. Movements and

Figure 1. Construction site showing terrestrial area and substructure, Karlsruhe, Germany (source: V. Sredić private photo)

relocations of structures are evident when factories are analysed over the decades of their existence. As Ridgway et al. *(*2013) note, change is normal, but the outcomes are unknown. The authors raise the following questions: "What developments can be expected in the physical arrangements of the 'factory of the future', i.e. would it be centralised, distributed, or reconfigurable?" "Have you witnessed such arrangements being effective?" "How does this differ by sector?" The authors suggest the following answer: "The physical arrangement will depend on the various needs and requirements and it is clear that there is no one answer that fits all" (p. 19). Lifecycles of industrial sites and changing transformation requirements need to be considered (Sredic, 2018).

The potential of maritime and floating structures: The potential of maritime structures is of particular relevance here. In the maritime world, the diverse advantages of floating structures are well-documented (Scanlan, 1974; Wang & Wang, 2015; Wang et al., 2020). Scanlan (1974) provides several insights into what is possible with floating structures, but this pioneering work receives little attention. According to Simović et al. (2020), the "water environment also brings a completely new perspective: it changes the way we act, feel and move . . ." (p.143). "Bionic, fractal and holonic manufacturing" (Tharumarajah et al., 1996) and sustainable urban factory habitats are becoming a realistic option, because floating structures enable organic transformations and growth (Scanlan, 1974; Wang et al., 2020). According to Wang et al. (2020, p. xi), "floating structures are a disruptive technology to address issues of land scarcity, degradation of coastal ecosystems, climate change, rising sea level and ocean acidification." Lim (2020, p. 391) concludes that "attractive candidates for floating out include transshipment ports, power stations . . . data centres, hydrocarbon storage, tanks, prisons, vegetable farms [etc.]", and Wang et al. (2020, p. xiv) similarly identify "floating wind turbines, . . . floating shipyards, floating airports and floating cities." Lim (2020) suggests that "many prime sites in the industrial zones currently occupied by ageing, dirty and increasingly irrelevant and uncompetitive industries should be recovered and repurposed" (p. 390), while Lim (2020) poses the question "what if we floated on sea instead of consuming land inefficiently?" (p. 19).

Michailides et al. (2013) analyse a modular floating structure with flexible connectors, discuss the "structural integrity of the floating system" (p. 117), and make clear that its interplay with its environment is crucial. Wang et al. (2020) provide knowledge about connected modular structures and fluid-structure interaction, considering wind, waves and other forces. Otto et al. (2020) provide relevant insight in terms of a model of a floating island that consists of interconnected pontoons, and its behaviour. "Varying global design parameters such as draft, assembly shape, module shape and module size" will be considered in the authors' future work (p. 188).

Compared to today's factories, the transformability of TAS-based factories is increased significantly in marine environments. Structures can be moved, relocated or removed. Construction, production and technical infrastructure related shapes, forms, functions and interfaces are more transformable and decoupleable from one another. TASs provide pluggable interfaces to diverse structures and open the door to new cooperation models and machine and energy generation concepts. Furthermore, TASs lead to increased transformability, and through transformations, efficiency can be retained. Lim (2020) also recognises the benefits of pre-producibility, increased transformability and more rapid and easier transformations with less disruption and fewer and shorter interruptions to ongoing operations. Overall, the transformability of floating structures and their benefits are increasingly recognised. "As floating structures are mobile, it is possible now to relocate used office buildings, residences, hospitals and factories to less developed countries for another cycle of productive life instead of demolishing it. This means building materials would be used more sustainably and their source material be less rapidly depleted. Living over water also means not having to build highways and railways with beneficial effects on the planet (Wang et al., 2020, pp. xi-xii)."

Simović et al. (2020) also suggest transformability will be of increasing significance because of global developments and humanity's changing lifestyles, behaviours and actions i.e. the way in which humankind lives, behaves and acts. The authors also describe the potential and ability of mobility, relocation, reconfiguration, continuous operation, preparation and preplanning of structures. They argue that "we need to start reconsidering architecture, and planning as well: rather than unchangeable structures with one constant function situated on a permanent location, we need to redefine the meaning of mobility within architecture" (p. 412).

Summary: The obvious problem of non-transformable areas is not questioned by mainstream research on factory planning, because terrestrial areas are taken for granted. This means that the use of building land is not questioned, but taken as given and set. When taking a closer look at long-term factory developments, it quickly becomes clear how serious the problems are in terms of transformations of static land-based factories etc. A building displacement with subsequent new construction at the same site and layout position can take five years or more (consider also moves, substitutions, limited space etc.). An existing factory configuration determines subsequent configurations and, more importantly, the necessary intermediate steps to the next targeted configuration. This leads to confusion, high complexity and compromises which lead to suboptimal processes.

The underlying assumption here is that the gap in factory planning is real and of significance because there is a gap in related theory and practice. The transformability of terrestrial areas is far behind the transformability of TASs both of which require further development and definition, as do their implications/impacts. The complexity and variability of this still very young and hardly researched subject area is considerable. It is assumed that there will be noticeable differences regarding the potential for TAS developments, relating to site availability, planning, implementation (greenfield), transformation (brownfield) and lifecycle. There will also be a wide range of challenges if TAS developments are to prosper, concerning impacts on standards, norms and laws, circular economy, digital technology deployment, sustainability and cost-benefit analysis assessments.

In this context, the following research questions (RQs) are addressed in this article:

RQ1: What is the potential of TASs and TAS-based uses?
RQ2: What are the key issues relating to the implementation of TASs and what are the likely future outcomes?

RESEARCH METHODOLOGY

The research methodology is mainly based on an integrative literature review (Torraco, 2016), the analysis of real-world factory developments, and elements of grounded theory (Corbin & Strauss, 2015). The research paradigm is realism (King & Horrocks, 2010) and a combination of inductive and deductive approaches are adopted (Easterby-Smith et al., 2008). Developing, defining and integrating new knowledge are key elements of this methodology, as is provoking, enquiring and questioning the world as it is today. In addition, a further conceptual development of the maritime TAS concept is pursued. This was done on the basis of various factories/factory layouts, transformations that have taken place in the past and several future redesigns that are currently being planned. Conceptual scenarios of possible uses were also considered.

In addition, interviews (Patton, 2002; George, 2023) were conducted with twelve experts and specialists: two environmental engineers, one electrical engineer, two naval architects, one structural engineer, an expert for the development and design of floating structures and continuous-flow machines with a work experience of more than 30 years, three project leads, and two project experts. All had work experience of eight years or more and were either involved in marine engineering, maritime engineering/offshore construction and/or other maritime technologies and uses. The selection of interviewees was based on relevant competencies where the author was confident that the required information could be obtained. Their specialist knowledge coupled with their respective industry experience were reasons for their selection. Assurances were given that the anonymity of respondents and organisations would be respected.

The main topics of the interviews were related to RQ1 and RQ2. The main categories were greenfield, brownfield and lifecycle of both land-based and maritime TAS-based factories, and TAS deployment and potential. Thus, "site availability", "planning", "implementation", "transformation", "transformability" and "lifecycle" were topics to focus on. The questions were related to these categories and were open questions in which the interviewees could describe these in the light of land-based factories and TAS-based factories. "Deployment feasibility", "operational capability", "uses" and "likely future outcomes" were additional categories for further questions about TASs and TASs-based factories. The questions were deliberately kept simple and followed the same logic: "What can you say about [category] in the context of [topic]?" Variants included "What is there to say about [category] in the context of [topic]?" Table 1 shows how the interview questions link to the RQs.

The interviews were conducted online via video conferencing tools. Where required, follow-up questions were asked. The data was analysed and structured to address the research questions. Where required, the data was afterward discussed via phone or video call (e.g. aspects which required additional clarification or justification). Thus, the reliability of the data was validated, as were findings and conclusions. In addition, several conversations were held for the exchange of knowledge, some of which involved factory planning and industry experts, and managers. Again, the data was then discussed via phone or video call where required. The content and feedback from these interviews and conversations were used to develop and validate the arguments put forward in this article.

FINDINGS

TAS Concepts

TASs involve modular and transformable substructures and superstructures. **Substructure** refers to all areas, objects and structures up to the ground level of the factory building, and **superstructure** the

Table 1. Links between interview and research questions

Interview questions followed this logic:			
What can you say about [category] in the context of [topic]?			
TOPIC		**CATEGORY**	**RELATES MAINLY TO RESEARCH QUESTION (RQ)**
land-based factories		Site Availability	RQ1
TAS-based factories		Planning	RQ1
		Implementation	RQ1
		Transformability	RQ1
		Lifecycle	RQ1
TOPIC		**CATEGORY**	**RESEARCH QUESTION (RQ)**
TAS-based factories		Deployment Feasibility	RQ2
TASs		Operational Capability	RQ2
		Uses	RQ2
		Likely Future Outcomes	RQ2
Information: All categories also provided information for addressing the other RQ.			
Transformable Area System (TAS)			

elements above ground level. TASs need to provide additional spaces and have at least one functional layer for substructures. This is indicated in Figure 2, where the first substructure layer is for supply and disposal infrastructure, and the remaining spaces in this layer allow for the integration of objects and structures into the ground/substructure. The base layer can be also used to some extent as additional space for machines and other objects and structures. **Structures,** then, is an umbrella term for areas, objects, substructures and superstructures. The **general structure** involves the dimensions, shapes, positions and connections of the main areas, objects and structures of a factory (or other type of structure). Thus, the general structure involves the arrangement and linking principle of all areas, objects and structures; this relates to the whole factory and its structures relevant for factory flows, e.g. traffic, material flows, and production flows.

Transformability is both a characteristic and a capability of factories. When a structure is transformable, it is able to adapt, e.g. to disconnect and change its configuration. Transformability can enable factory transformations such as building extensions and the movement or relocation of structures. The transformability of factories can be made possible by **transformation enablers** (Hernández, 2002; Wiendahl et al., 2015), which are the characteristics and capabilities of areas, objects and structures that determine their transformability. They include their modularity, mobility, pluggability, scalability, universality and linking ability. The linking ability enables different relationships, flows and statuses inside and outside of factories. Areas have recently been added to this and other definitions and related concepts etc. have been developed. **Fundamental enablers** are the area size, area shape, and movable area size (MAS). The MAS indicates the area that can be moved and whose shape and other properties can be adapted as required. Substructure characteristics and capabilities are also fundamental enablers (Sredić, 2018). **Accelerators** refer to characteristics and capabilities of areas, objects and structures that accelerate the planning, implementation/ construction and/or transformation of factories. Pre-producibility, pre-testability, and reusability, for instance, are accelerators (Scanlan, 1974; Hildebrand, 2005). If an accelerator can be combined with an area, object or structure, an acceleration unit is created. Acceleration units, especially when combined with fundamental enablers, impact on factory planning processes and transformability, and on implementation and transformation velocity. **Inner mobility** refers to the ability of moving different areas, objects and structures within one location, whereas **outer mobility** is concerned with the ability of relocating areas, objects and structures to new sites (Wirth et al., 2000). **Inner and outer transformability** increase the complexity of transformability and transformation planning, and the potential. Inner and outer transformability require the consideration of the other enablers, accelerators and related units. **Agility** refers to the required dynamics of factories, production networks and other networks. It considers the environment of factories and such networks (Wiendahl et al., 2015), and can be associated with the capability of areas to meet the aforementioned dynamics.

The Potential of Maritime TASs (RQ1)

As noted above, the number and extent of floating structures are increasing (Blue Frontiers, 2018; Wang et al., 2020; Herwig, 2021), and the enormous potential of water bodies and areas for advanced, flexible and transformable construction is just beginning to be recognised. The advantages of maritime TASs over land-based factories are becoming increasingly evident (Table 2). There is agreement that site availability of maritime TASs is potentially high and that of land-based factories is restricted in most developed economies. However, environmental issues in particular need to be addressed. With regard to planning, implementation, transformation, and lifecycle, there is also agreement (summarised in Table 2). Further conversations with factory planning and industry experts and managers showed that real-world examples of factory projects are not lacking and that these further validate Table 2, i.e. the greenfield, brownfield and lifecycle disadvantages of land-based factories and the potential of TAS-based factories. This section outlines the characteristics, capabilities and potential impacts of the maritime TASs. One example of a maritime TAS is Bluefield®, which is still a mainly theoretical construct, and has yet to be implemented in practice. It is a proposition that builds on certain existing physical structures and possibilities.

A maritime TAS involves different modular functional layers and an integrated modular supply and disposal infrastructure, as depicted in Figure 2. Maritime TASs can be seen as sophisticated floating pontoon systems, with several layers and the possibility of coupling with other TAS elements. Maritime TASs involve modular and mountable (integratable and disintegratable) layers, form fit connections, connectors and drives. They are, in general, more complex than most existing maritime/floating structures or systems that consist of modular and combinable pontoons. Simple pontoon systems and other floating structures have often only one layer which is the floating element(s) itself, i.e. the floating body or pontoon. Coupling with other floating elements is possible, but not the integration and passage of pipes, cables, etc. throughout the single and combined elements, as is possible with TASs. In addition, with TASs, individual layers or areas/parts of these can be coupled and exchanged.

Figure 2. Conceptual sketch of a TAS element(s) with substructures and superstructures

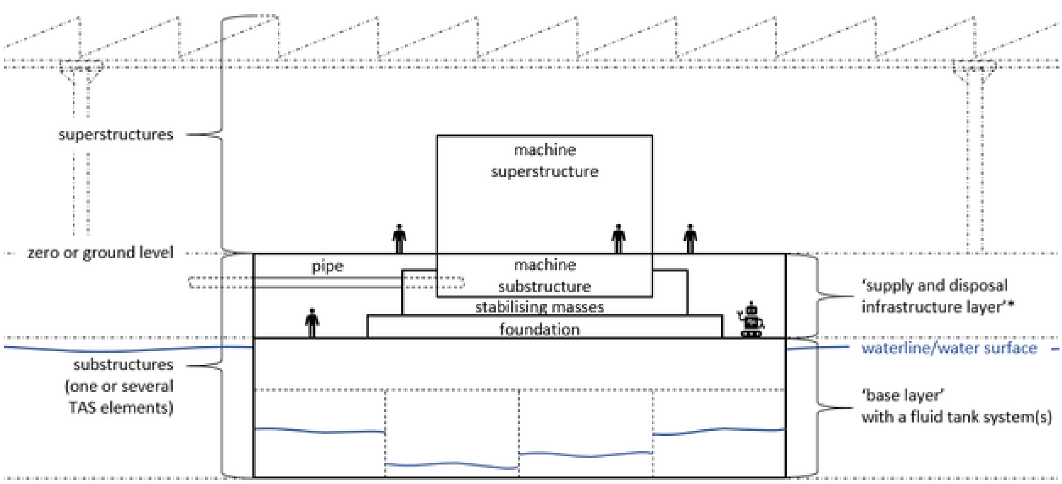
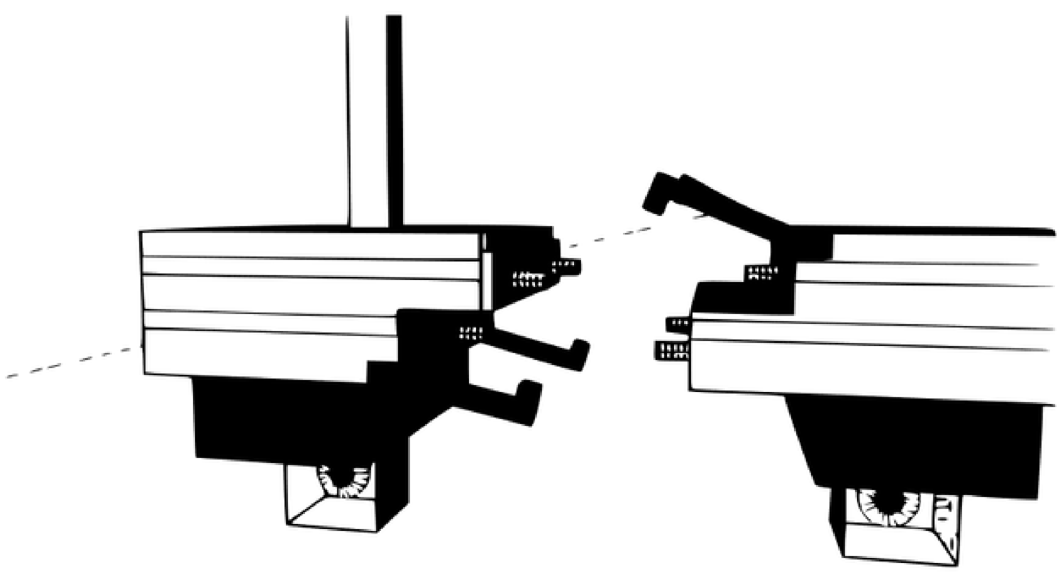


Table 2. Land-based factories and Maritime TASs: comparison of key aspects

Comparable	Land-Based Factory	Maritime TAS-Based Factory
Site Availability	Severely restricted in most developed economies	Potentially high, but environmental issues need addressing
Planning	Complex and cumbersome (especially in the case of Brownfield projects)	In general, this should be simpler, once legal and environmental issues are addressed.
Implementation (Greenfield)	Dominated by earthworks and construction works	Can benefit from pre-producible, pre-testable, reusable, scalable and otherwise highly transformable areas, objects and structures
Transformation (Brownfield)	Dominated by earthworks, construction works and demolitions; Difficult to transform	Relatively simple to transform and sustainable, because of potential reuse or replacement of areas, objects and structures
Lifecycle	Inflexible and not sustainable; dominated by displacements, demolitions, substitutions, and inefficient processes	Flexible and highly sustainable

An advantage of maritime TASs is that the upper or top layer(s) can be kept away from water, at least to some extent. Water is touched by the base layer which includes a fluid tank system and makes the system buoyant. The supply and disposal infrastructure layer has openings and is modular. The associated layer elements can also be modular. Seals, systems, devices and elements that support diverse functions complement the essentials and basic features. Coupling mechanisms and various connectors are required. For clarity, these are only shown on one side of the elements. In addition, details have been removed and proportions changed (Figure 3). Further capabilities and characteristics will necessarily be developed, as the TAS concept and product evolves, and the number of TAS requirements profiles will increase and be further differentiated in the future, as will uses and their requirements. ‘Transformability and transformation planning’ is complex and essential, and should no longer be seen as a part of factory planning only.

Figure 3. Simplified elements of a maritime TAS



TASs may require earthworks for their dock(s) or connection(s) to the shore. Several floating TAS elements form one or more transformable areas that can be used for numerous purposes being multifunctional, or for specific purposes. They can be combined with modular building concepts and other advanced objects and structures. Maritime TASs enable the exploitation of water bodies and areas, enabling active transformability and transformations. Outcomes are new dimensions of transformability and new opportunities. In this regard, fundamental enablers are key, e.g. different MASs, shapes and area and substructure characteristics and capabilities that can easily be changed. Transformability and implementation and transformation velocity are significantly increased. This engenders competitive advantages and the sustainability of industrial and other structures that can accommodate flexible lifecycles. Combinability is almost unlimited in the case of TASs. Small and large TAS satellite units, that are scalable can be monitored, maintained and transformed over time, and can also be combined with other areas and uses. This opens the door to so far unachievable and unexplored synergies. Once in place, maritime TAS-based factories are more competitive than today's factories, offering new possibilities with regard to pre-producible, pre-testable, reusable, exchangeable, scalable and otherwise highly transformable areas, objects and structures. Planning, implementation and transformation processes are likely to be simpler and speedier than land-based comparables, while structural capabilities provided by TASs are advantageously supported and accelerated by digital capabilities.

In summary, the advantages of maritime TASs and structures include:

- Transformability is increased and transformations are simplified.
- They provide a transformable framework for sharing common services, which can be retained or adapted, consisting of supply and disposal facilities and infrastructures, and transportation infrastructures.
- Increased and new dimensions and forms of structures and products are possible. Structures can be pre-produced, assembled and placed on TASs.
- Lifecycles of structures are flexible and sustainable, and characterised by high operational, energy, and resource efficiency.
- Combinations of uses and potential synergies are increased.

Key Issues and Future Outcomes (RQ2)

The above review of literature and presentation of the maritime TAS concept raise a number of issues regarding the future deployment of TASs.

Firstly, despite their potential, maritime concepts and solutions can be complex, and *maritime TASs pose a number of challenges*. The inter-relationships of user demands, structural requirements, structures, design and other matters related to floating structures are key. Connections between floating elements and layers lead to design and operational complexity and have an impact on the design and sizes of structures, and later operation. Other matters need to be considered in the further development and implementation of maritime TASs for different uses, even though complexity might be decreased through other connectors, the diversion of water, the use in calm waters and/or the use of seawalls, waterfronts, breakwaters and/or other structures to reduce and/or dissolve wind, wave and other impacts, some of which are described in Wang et al. (2020). Connections between different elements are one main issue, as are forces and their impact on maritime structures (and vice versa). TASs lead to additional challenges due to the extra layers. The challenges arising from the interplay of different factors in the design of modules and parts can be addressed or solved using current and new technologies, while use specifications impact on design and solutions, which per case decide which connectors are required at which positions. In addition, legislative and insurance issues will need managing. Maritime TAS may have an impact on existing maritime standards, norms and laws. This is partly due to the new possibilities in terms of area sizes, mobile or movable area sizes (MASs), and transformable or changeable MASs (i.e. simultaneously moving and changing areas and structures). In addition, new dimensions and sizes of objects and structures, and new uses will be made possible. All this has to be thought through and defined. Pre-productivity, pre-testability and re-use will also play their part in defining new necessities in terms of law etc. which will be challenging. Real-world examples of TAS-like structures can be found in Wang & Wang (2015), Sredic (2018), Wang et al. (2020) and Du et al. (2023). Nevertheless, further analysis and development is required.

Secondly, *TASs deploy and will rely upon digital technologies,* and can be seen in the context of digital transformation and associated change processes (Wynn, 2022). Digital factory, business information modelling, virtual reality, augmented reality, other digital and computerised solutions, AI and diverse Industry 4.0-related achievements can be effectively deployed in the planning, visualisation, simulation, implementation, transformation, operation and/or management of TASs. One example is the use of hardware and software to identify relevant positions and interfaces, e.g. for motions of objects taking into account their functions, dimensions and masses. To use AI and Industrial Internet of Things devices or objects and structures "without human intervention" (Boyes et al., 2018, p. 3) is more possible with TASs, e.g. for directing, navigating and controlling. They can even include themselves among these objects and structures, and contain and carry others. Structural capabilities provided by TASs are advantageously supported by digital capabilities, e.g. for autonomous transformation. This opens the door to an era of increased automation, autonomy, self-sufficiency, efficiency, effectiveness and environmental relief, simultaneously using environmental potential in a new form and level, which for the large part is in line with authors from the maritime field (consider networks and cooperation). The potential of Industry 4.0, digitalisation, AI and other technologies etc. increases with TASs, and vice versa. For example, McKinsey (2023), suggest that "quantum computers are poised to take computing to a whole new level", and IBM (2023) argued that "this technology is widely expected to solve valuable problems that are unsolvable using any known methods on classical supercomputers." Such increases in computing power will speed the onward progression of TAS projects. Even though digitalisation and digital twin technology are still in their infancy (Wynn & Irizar, 2023), this is expected to further increase the potential of TAS-based factories and applications. This is due to the increased transformability (e.g. modularity) and thus the significantly improved ability to integrate and disintegrate individual objects and structures, to name just one example. This is in line with Boyes et al. (2018), who concluded that numerous connected devices can lead to advantageous behaviours in the light of the needs of their environment. Autonomous floating platforms and systems are already in use and further developed in research (Veigel, 2021; Du et al., 2023).

Thirdly, *TASs impact on factory planning and construction norms*. Increased capabilities provided by TASs are crucial. Numerous advantages are possible compared to the current status. This can be understood when large projects and related needs are analysed, and applies also to other than factory projects, e.g. the Stuttgart-Ulm rail project (DB Projekt Stuttgart-Ulm GmbH, 2020) in which very large inhibitors such as large terrestrial areas, infrastructures and concrete structures in the city centre and other urban areas require a chain of necessary but questionable actions. The applied traditional paradigm in implementing such projects is far away from being lean and effective. Infrastructure, urban and factory implementation and transformation projects are relevant in this context, many structures of which will experience numerous transformations throughout their lifecycle.

Complexity and planning effort are decreased. Factories and projects are more manageable. The potential impact of TASs on (factory) planning processes, implementation and transformation velocity, and factory characteristics and capabilities throughout factory lifecycles is considerable. Requirements and processes are more easily defined; transformations and growth are simplified. Agility can be achieved at a new level.

Fourthly, *TASs are of relevance to the current debate on the circular economy, and the broader sustainable development agenda.* Wynn and Jones (2022) examine the relationship between digital technology and sustainability, and discuss potential future research in this context. Furthermore, artificially manufactured structures have more mass than all living beings (Deutschlandfunk, 2020). This highlights the increasing importance of the transformability of structures. TASs mean that physical structures can be more transformable. Terrestrial areas can be freed for other needs and uses, which is in line with Wang et al. (2020) and Glaubrecht (2021), as far as environmental risks are eliminated, reduced and/or kept under control. Several risks are discussed in Yusuf and Abdulmohsen (2022). Possible solutions for sustainable cities such as those related to revolutionary multi-water systems (Nakajima & Umeyama, 2020) are only one example showing that TASs with their integrated supply and disposal infrastructure are relevant to transitioning to a sustainable world. New and upcoming technologies, technical solutions and materials can be involved in TAS developments, such as those provided by the German Research Institute for the Textile Industry (DITF). There are issues with TASs of site availability and their environmental impact. These are valid concerns. Calm waters are preferred for effective operation of TASs, given the requirements for buoyancy, safety etc. Coasts near towns and cities are already used by industry and this could be a good starting point to gradually implement TASs. The paradigm and patterns of industrial structures, i.e. how they are seen, could change with TASs and other maritime structures. This could accelerate their use if safety and environmental matters are appropriately addressed.

Fifthly, the *cost-benefit equation for TASs will re-balance in favour of net benefits in time*. Key barriers to implementing TASs include the large initial investment that is required. In addition, the necessary competencies to develop TASs further are manifold, and a short-term return on investment is not realistic for the initial TAS development phase. However, price will decrease when TASs become productised and standard, as global requirements increase in future. The increasing costs of environmental degradation, demolitions and construction works will also help re-balance the cost-benefit equation. The total cost of ownership (TCO) of TASs will reduce and they represent a high cost-saving potential long-term, while the TCO of today's factories is high and increases over time, because more resources and demolitions will be required, and reuse is very limited. This is in line with Lim (2020), who describes different uses that can be based on maritime structures and argues: "They have to understand that a float is an asset, not an expense. It has a life of more than 100 years and will have a substantial market value even if it is written down completely in the balance sheet. That value arises from the fact that unlike land-based real estates, it may be repurposed and deployed" (p. 391). TASs will become increasingly relevant and necessary (Figure 4).

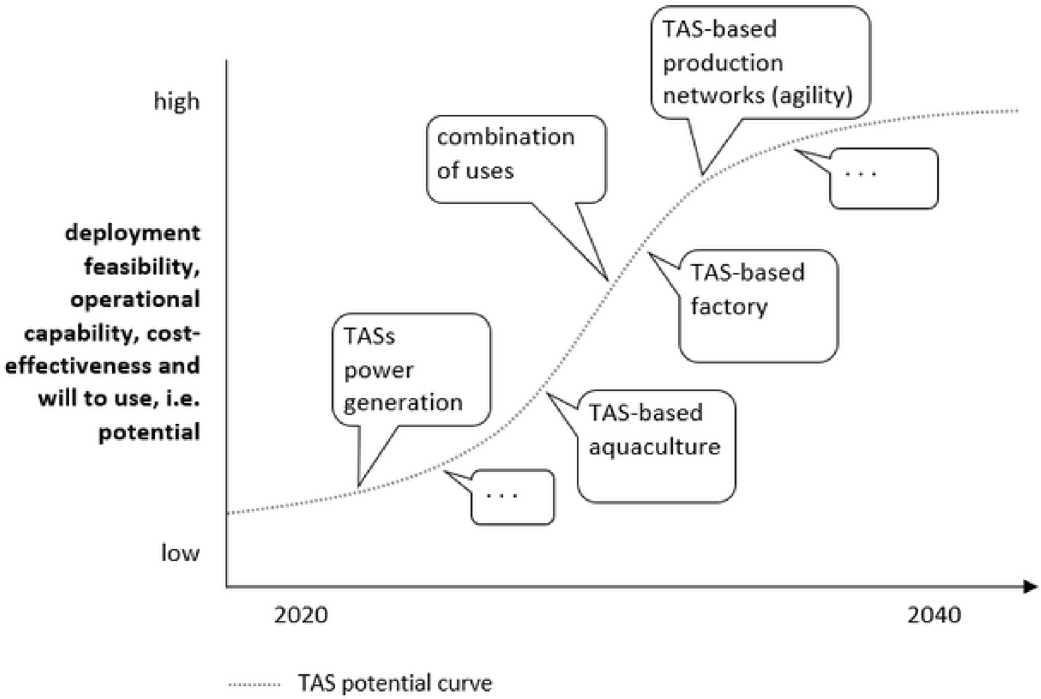
Figure 4 depicts the possible deployment of TAS-based uses in general and the overall TAS potential curve. Operational capability will increase over time because more knowledge and experience will be available. With increased deployment, the cost will decrease and the perceived benefits will increase. The protection of nature and water bodies is a key issue that must be managed sustainably.

Economic analyses and cost estimates of diverse floating structures, pontoons etc. abound in the literature, and various companies and start-ups also repeatedly show that an investment in such solutions can be worthwhile (Lim, 2020; Masterson, 2021; Heliorec, 2023; Hansa, 2023; Neom, 2023). An overarching approach may be more effective than trying to achieve economic efficiency with individual applications within current system settings. The literature mentions the long lifespan of several maritime structures as a major advantage. All interviewees confirmed this advantage, and maintained that this advantage, in combination with increased transformability, makes long-term use even more possible. The increased initial investments can be broken down and capital assets can be depreciated over the long-term.

The interviews showed that breaking out of the current system settings is hardly possible at present and that short-term profits often result in solutions that are far from optimal in terms of sustainability and nature conservation. How sustainable products and solutions can be pursued against the background of current system settings and consumer behaviour remains open and requires further research. Changes in global government regulations will likely be necessary for such a transition.

Power generation is an indispensable and essential part of the TAS potential curve, and different energy sources need to be considered, not least because of the growing global population, and

Figure 4. Deployment of TAS-based uses and TAS potential curve



consequent energy, food and product demands. TAS-based energy generation is a possible development and further investigations and technical developments are necessary here. Combinations of uses require further analyses. The interviews suggest that a combination of power generation, factory and habitat could be a realistic possibility.

The motivation for writing this paper is to reveal the potential of TAS-based developments, even though a lot more work needs to be done here. This requires a collective effort because of the complexity, probable importance, potential and risks of TASs and similar structures. Attitudes that focus solely on profit-orientation and short-term thinking need to change to promote and enable sustainable behaviour. This is a field in which politics, economics and law must work together to effect such change.

CONCLUSION

This article has set out the potential benefits maritime TASs offer for factory planning and development, and the wider implications of TASs for sustainability and future viability. The key barriers to implementing TASs have been explained. To overcome these barriers is difficult, but several aspects increase the probability that TASs will be implemented. Ridgway et al. (2013, p. 6) argued that "the design of agile, reconfigurable factories and extended enterprises" is vital for the factory of the future. However, agility is not applicable in the case of existing factories and other building land-based uses, but *is* an option with TASs and TAS-based uses: agility, transformability, flexibility, structuredness, effectiveness, efficiency, multi-use and synergies potential, sustainability and future viability are increased, very high, and can be retained.

The flood of mainstream literature on the factory of the future and Industry 4.0 highlights a range of future requirements but no serious idea how to address them. TASs are undoubtedly complex. Nevertheless, the concept is worthy of support because of their potential. Different areas of competence must come together to develop maritime TASs further. Interdisciplinary teams will be necessary. Research on TASs, TAS-like and TAS-based structures and planning is in its infancy and requires collective effort. Available and new technologies, technical solutions and materials can be used for the further development of TASs etc. Some of them can be scaled up and combined with other technologies and solutions.

Future research initiatives could examine how transformability can be assessed and increased, and factory, transformability and transformation planning could be considered in the context of maritime and terrestrial developments. The potential of TASs and related planning and theory are relevant for research and innovation programmes such as Horizon Europe, for example, for climate neutral and smart cities. Further technical development, analyses of legal and environmental feasibility, and further definition of possibilities, advantages, disadvantages and risks will be required. TASs are a realistic possibility, as similar but less complex structures are already being implemented, but with similar risks. Established disciplines should evolve to accommodate the TAS concept, including architecture, urban and factory planning, professional project management and environmental engineering. Further works could consider how TASs and digitalisation, AI and Industry 4.0 can benefit from one another in detail.

TASs have the potential to make a disruptive and positive impact on physical structures, and on their planning, implementation, transformation, relocation, operation, management and lifecycles. This is a radical viewpoint that suggests TASs can contribute to sustainable cities, advanced production and products, factories and production networks, and other advantageous structures and uses. We live in an environmentally connected world, and the transition to green thinking and action must be initiated, supported and promoted by appropriate authorities and governments. It is hoped that this article may create some small impact in fostering this ambition.

ACKNOWLEDGMENT

I would like to thank Professor Doctor Martin Wynn for his support through the years. Furthermore, I would like to thank Andreas Petzoldt (Mewatec), Professor Doctor of Engineering Patrick Balve, Marc Llistosella Y Bischoff and Professor Emeritus Doctor of Engineering Mathias Paschen.

COMPETING INTERESTS AND FUNDING STATEMENT

The author of this publication declares there are no competing interests.

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. Funding for this research was covered by the author of the article.

KEY TERMS AND DEFINITIONS

Accelerators: Characteristics and capabilities of areas, objects and structures that accelerate the planning, implementation/construction and/or transformation of factories. Pre-producibility, pre-testability, and reusability, for instance, are accelerators.

Agility refers to the required dynamics of factories, production networks and other networks.

Brownfield is a factory (re)planning and transformation project with current objects and structures.

Fundamental enablers: The area size, area shape, movable area sizes (MASs), and area and substructure characteristics and capabilities.

Greenfield is a new factory planning project without any current objects and structures, e.g. buildings.

Inner and outer mobility: Inner mobility refers to the ability of moving different areas, objects and structures within one location, whereas outer mobility is concerned with the ability of relocating areas, objects and structures to new sites.

Maritime Transformable Area System: Involves different modular functional layers and an integrated modular supply and disposal infrastructure, and is therefore more complex than existing maritime/floating structures or systems that consist of simple modular and combinable pontoons.

Structures is an umbrella term for areas, objects, substructures and superstructures.

Substructure refers to all areas, objects and structures up to the ground level of a factory (or other type of structure). This will likely include foundations, pits and below ground technical infrastructure.

Superstructure(s): The zero or ground level is the border and interface between substructures and superstructures.

Transformability is both a characteristic and a capability of factories. When a structure is transformable, it is capable to adapt, e.g. to disconnect and change its configuration. Transformability can enable factory transformations such as building extensions and moves/relocations of structures. The transformability of factories can be assessed with transformation enablers

Transformable Area Systems (TASs): Areas that involve substructures, e.g. elements of the supply and disposal infrastructure. TASs can also be used as transportation infrastructure, and be combined with modular and transformable substructures and superstructures.

Transformation enablers: Characteristics and capabilities of areas, objects and structures that determine their transformability. Transformation enablers are the modularity, mobility, pluggability, scalability, universality (i.e. function and utilisation neutrality), and linking ability (i.e. interconnectivity). The linking ability enables different relationships, flows and statuses inside and outside of factories.

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