Current status, advancements and development needs of geospatial decision support tools for marine spatial planning in European Seas

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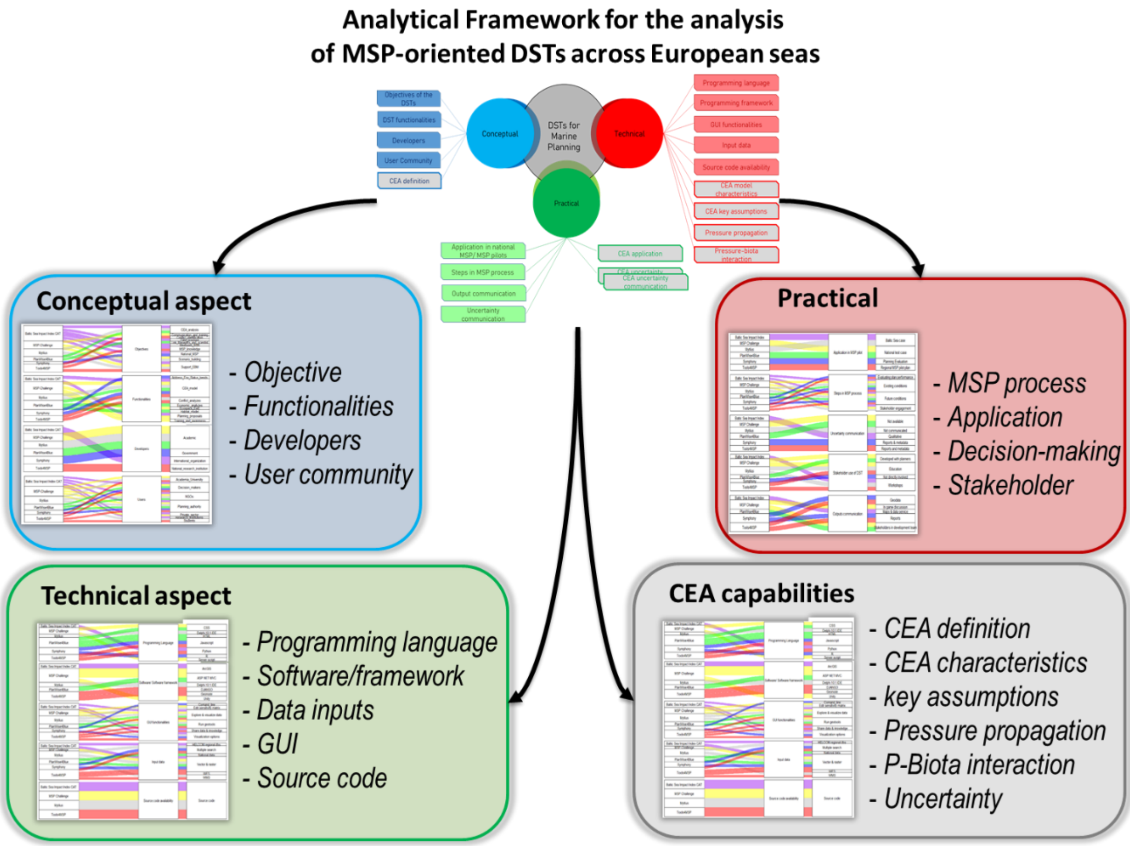
Keywords: Decision Support Instruments; Geospatial tools; Maritime Spatial Planning; Ecosystem-based Management; Cumulative Effects Assessment

Abstract

The implementation of marine spatial plans as required by the Directive on Maritime Spatial Planning (MSP) of the European Union (EU) poses novel demands for the development of decision support tools (DST). One fundamental aspect is the need for tools to guide decisions about the allocation of human activities at sea in ways that are ecosystem-based and lead to sustainable use of resources. The MSP Directive was the main driver for behind the development of spatial and non-spatial DSTs for the analysis of marine and coastal areas across European seas. In this research, we develop an analytical framework designed by software developers and managers for the analysis of six DSTs supporting MSP in the Baltic Sea, the North Sea, and the Mediterranean Sea. The framework compares the main conceptual, technical and practical features by which these DSTs contribute to advancing the MSP knowledge base, and identified future needs for the development of the tools. Results show that all of the studied DSTs include elements to support ecosystem-based management at different geographical scales (from national to macro-regional), relying on cumulative effects assessment and functionalities to facilitate communication at the science-policy interface. Based on our synthesis we propose a set of recommendations for knowledge exchange in relation to further developments, mechanisms for sharing experience among the user-developer community, and actions to increase the effectiveness of the DSTs in MSP processes.

Graphical Abstract



Highlights

- Six DSTs for MSP were analysed
- An analytical framework is designed and used for comparing the DSTs
- DSTs are multi-objective by nature
- Cumulative effects assessment (CEA) is the most recurrent tool implemented in the DSTs
- Operational recommendations for further alignment and improvement of the DSTs are provided

1. Introduction

The relatively new practice of maritime spatial planning (MSP) poses novel challenges in the design and development of Decision Support Tools (DSTs). New tools capable of guiding planners in ecosystem-based management and foster sustainable use of marine resources are needed. In the European Union, the Maritime Spatial Planning Directive is a strong driver of the development of such tools (EC, 2014). Similar challenges in terms of achieving environmental and socio-economic objectives are seen in many other coastal and marine areas of the globe (Guerreiro et al., 2020; Finke et al., 2020; Gerhardinger et al., 2019).

While several definitions for DSTs within environmental planning were proposed for agriculture (Rose et al., 2016), river basin management (Welp et al., 2001) or environmental risk and impact assessment (Sullivan et al., 2002), a MSP-specific definition of a geospatial DST has not yet been developed.

For the purpose of this research, we adopt a definition of a geospatial DST for MSP, based on Sprague and Carlson (1982) as an interactive system, that 1) is designed to analyse problems and processes relevant for MSP, 2) provides mechanisms to evaluate spatial and non-spatial data and information of different formats and sources, 3) represents spatial relations and structures in the sea and the adjacent land; 4) provides techniques for spatial and geostatistical analyses and processing; and 5) supports a variety of graphical output formats.

In the last decade, there has been a major increase of initiatives to collect, systematise, and share MSP-relevant knowledge, at the international, European (e.g. ICES, 2020; EMODnet, 2020; HELCOM, 2010; OSPAR, 2020) and national levels (RITMARE, 2017), Efforts have been made to develop spatially-explicit information systems to manage and process diverse geospatial information into structured and planning-relevant outputs (Kannen et al., 2016; Janßen et al., 2019). In parallel to this development, the research community has put effort in the advancement of specific functionalities of DSTs with different planning objectives. For instance, cumulative effects/impact assessment tools were developed to understand the ecological risks and consequences from anthropogenic activities at sea for vulnerable marine resources (e.g. Stelzenmüller et al., 2013; Murray et al., 2015). Software tools, such as InVEST (Integrated Valuation of Ecosystem Services Trade-offs) were developed to analyse the benefits that humans derive from nature (Guerry et al., 2012), including applications in the marine realm through Marine InVEST (msp.naturalcapital, 2020), such as tourism visitation rates (Cunha et al., 2018), coastal landscape scenic quality (Griffin et al., 2015) or wave energy provision (Kim et al., 2012). Other decision support tools such as MARXAN, were applied for the design of conservation strategies and biodiversity targets (Mazor et al., 2014) or for offshore wind energy suitability localisation (Göke et al., 2018).

The scientific community has strived to provide frameworks to review and evaluate DSTs for MSP to address their effectiveness within a decision-making process, incorporate stakeholder perception and guide future development priorities. For instance, Bolman et al. (2018) provided a framework to address objectives and development processes behind DSTs, with the final aim to understand their usefulness for marine management and decision-making. Pınarbaşı et al. (2017 and 2019) reviewed the most common DSTs and proposed a matrix to assess their purpose, gaps, functionalities in respect to different stages of the MSP implementation and end-user experience. Krueger and Schouten-de Groot (2011) assessed 118 MSP tools by addressing their functionalities, success factors and stakeholder needs, based on a predefined set of criteria elaborated through literature review and interviews. Kannen et al. (2016) provided a catalogue of spatial and non-spatial tools that addresses integration challenges in MSP, their strengths and weaknesses, and their basic conditions for application.

Notwithstanding the growth in literature, most of the studies lack a conclusion on how the efforts taken in research and the software development community have contributed to recent advancements in DSTs. In particular, alongside a generally increased demand for spatial analyses to support marine management, the EU MSP Directive was a significant policy driver for the development of marine data platforms and marine monitoring campaigns aiming at the systematic collection of geospatial data on human activities, and on ecological and physical features. As a result, manifold initiatives across European seas emerged in the last years that aimed to design geospatial information platforms oriented to MSP and ecosystem-based management (PORTODIMARE, 2020; SIMCELT, 2017; EMODnet, 2020).

In this research, we analyse the capabilities of six geospatial DSTs for MSP in the Baltic Sea, the North Sea and the Mediterranean Sea through the perspective of their developers. We used 23 criteria to analyse the conceptual (e.g. DST objectives, functionalities or user-developer community), technical (e.g. programming language, software framework, data input) and practical aspects (e.g. stakeholder engagement, DST application in MSP process) of the following six DSTs: Mytilus, Tools4MSP Geoplatform, Symphony, the Baltic Sea Impact Index (BSII), PlanWise4Blue (PW4B) tool and the MSP Challenge Simulation Platform including Ecopath with Ecosim. We paid particular attention to cumulative effects assessment (CEA) capabilities, a functionality that is present in all the screened DSTs. We conclude with a set of operational recommendations for a more coherent coordination of DST development for MSP on European scales, with the aim to strengthen synergies between developers and user communities.

2. Materials and Methods

2.1. *Surveyed DSTs*

Six DSTs supporting different aspects of MSP were analysed through the lens of the DST developers (Figure 1): Mytilus (Hansen, 2019), Tools4MSP (Menegon et al., 2018a and b), Symphony (Hammer et al., 2020), Baltic Sea Impact Index (BSII; Bergström et al., 2019), PlanWise4Blue (Kotta et al., 2020) and the MSP Challenge Simulation Platform(Abspoel et al., 2019). We selected these DSTs because (1) they were considered as the most long-lasting and advanced DST for MSP-oriented geospatial investigation applied at European level; (2) they were applied and tested across different stakeholder groups, including experts and non-experts, and at national and transboundary levels in their respective study domains; (3) they can be flexibly applied for both national marine spatial plans and macro-regional studies and (4) they all include a Cumulative Effects Assessment (CEA) tool in their functionality. Table 1 provides an overview of the six DSTs, in terms of application domains, the tools implemented and key references to the DSTs. To notice is that Mytilus and Tools4MSP incorporate also a Maritime Use Conflict analysis tool (MUC; Menegon et al., 2018) and Conflict-Synergy analysis instrument respectively. Also to notice is that both BSII CAT and Mytilus are applied in the Baltic Sea, Tools4MSP is applied in the Adriatic-Ionian Region (Mediterranean Sea), MSP Challenge Simulation Platform is applied in the North Sea, Baltic Sea and Firth of Clyde, while PlanWise4Blue and Symphony are applied on national level, respectively in Estonia and Sweden.

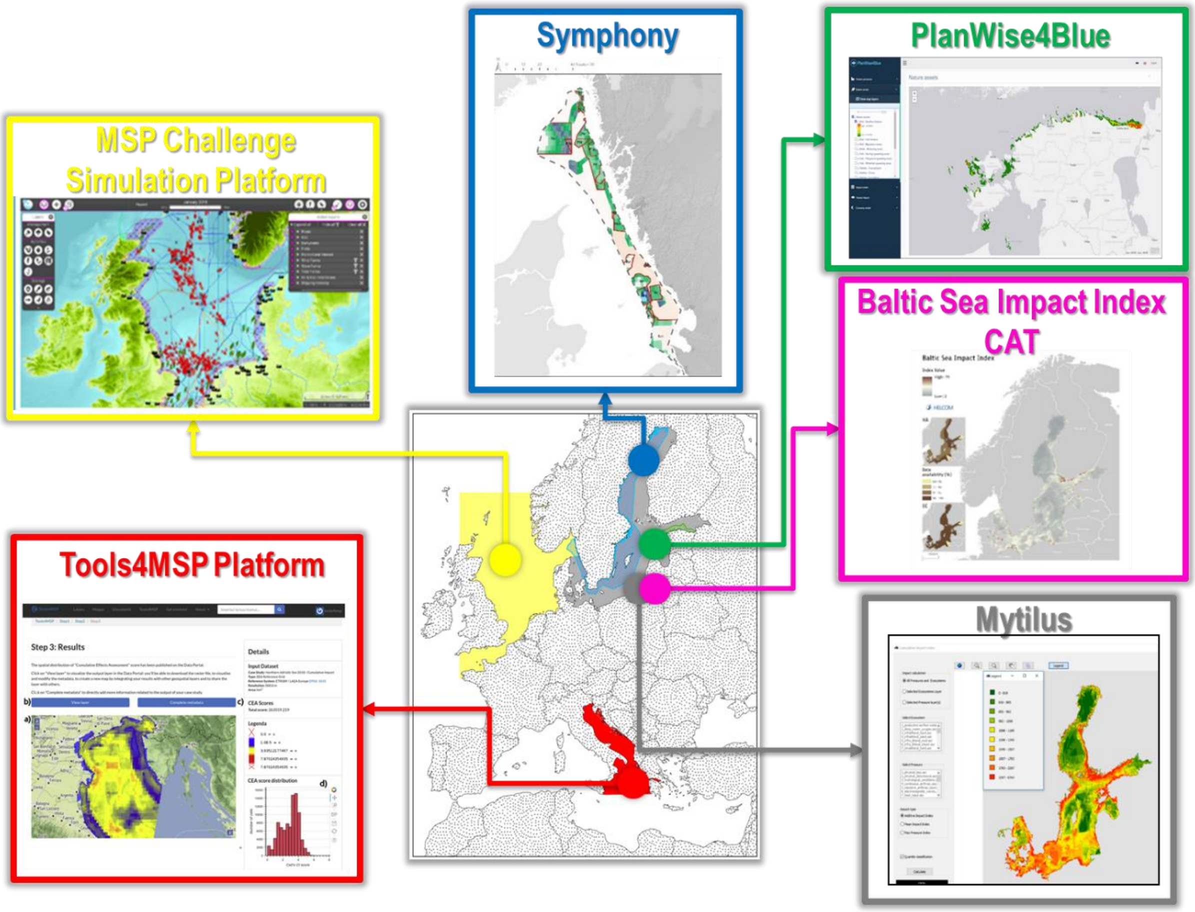


Figure 1. The six Decision Support Tools (DSTs) reviewed in this study including geographic areas of application.

Table 1. Summary of DST, their domains, purpose and key information sources. Note: CEA – Cumulative Effects Assessment, MUC – Maritime Use Conflict; C-S – Conflict and Synergy analysis.

DST	Application domain	Tools	Sources
Mytilus	Baltic Sea	CEA, C-S	BONUS BASMATI, 2020; Hansen 2019
Tools4MSP	Adriatic-Ionian Region	CEA, MUC	Menegon et al., 2018a and b; Farella et al., 2020; PORTODIMARE, 2020
Symphony	Sweden	CEA	Hav, 2019; Hammer et al., 2020
Baltic Sea Impact Index Impact Assessment Tool (BSII CAT)	Baltic Sea	CEA	Bergström et al., 2019; PanBalticScope, 2019

PlanWise4Blue	Estonia	CEA	PlanWise4Blue, 2020; Kotta et al., 2020
MSP Challenge	North Sea. Baltic Sea, Firth of Clyde	CEA	MSP-Challenge, 2020; Steenbeek et al., 2020; Abspoel et al., 2019

2.2. Overview of DSTs

2.2.1. Mytilus

Mytilus was developed at the Department of Planning, Aalborg University and aims at providing a rich set of tools fulfilling criteria such as ease of use, analytical capacity, and high-performance calculations (Hansen, 2019). Mytilus is a free open source stand-alone desktop application not dependent on other software or licenses, but using the same data models being used in common GIS software as ArcGIS and QGIS – i.e. shapefiles and ESRI ASCII grids. The development of the Mytilus toolbox started in the INTERREG North Sea project NorthSEE and is being further developed under the BONUS BASMATI (2020) project as a tool connected to the Baltic Explorer Platform (www.balticexplorer.eu). Although Mytilus is generic and can be applied in any geographic sea area, it is currently only used in the Baltic Sea and the North Sea in connection with the BONUS BASMATI and NorthSEE projects, respectively.

2.2.2. Tools4MSP Modelling Framework and Geoplatform

The Tools4MSP Modelling Framework is an open source software based on Free and Open Standard Software (FOSS) developed by the National Research Council – Institute of Marine Sciences (CNR-ISMAR, Italy). Tools4MSP has the aim to support MSP-oriented analysis through geospatial functionalities, such as CEA and maritime use conflict analysis in the Adriatic-Ionian macro-region (Menegon et al., 2018a; Depellegrin et al., 2017). The tool is accessible to users under two modes: (1) the stand-alone geopython library (code repository: https://github.com/CNR-ISMAR/tools4msp) and (2) the Tools4MSP Geoplatform (www.tools4msp.eu), for more user-friendly geo-tool applications. The DST has been developed since 2014, within national and EU-wide project clusters such as ADRIPLAN (ADRiatic Ionian maritime spatial PLANning, 2015), RITMARE (Italian Research for the Sea, 2017) and PORTODIMARE (geoPortal of Tools & Data for sustainable Management of coAstal and maRine Environment, 2020)

2.2.3. Symphony

Symphony is a tool developed within the Swedish MSP for assessing the cumulative environmental impacts of different planning options (HaV, 2018; Hammar et al., 2020). It also functions as a library of MSP-relevant data on marine ecosystems, including human pressures. The underlying data consists currently of 32 different ecosystem components and 41 different human pressures in a standardised raster format for the Swedish marine area. Its development started in 2016 and it was first applied in marine planning in 2018. Symphony is a collaborative effort of the Swedish Agency for Marine and Water Management (SwAM), that owns the tool, the Geological Survey of Sweden (SGU) who have coordinated data standardisation and many other organisations, whose role have mostly been as providers of data. It is currently only available to SwAM maritime spatial planners, but is planned to be available to municipalities and County Administrative Boards. The data has been publicly available since 2019. Symphony has been used to in the assessment of cumulative environmental impacts during the strategic environmental assessment of the plans and in the identification of suitable areas for precautionary measures. Symphony is also used in other areas of marine management in Sweden and as a component in multilateral collaboration projects. Work is ongoing to improve its climate change and ecological connectivity analysis capabilities.

2.2.4. The Baltic Sea Impact Index CAT

The Baltic Sea Impact Index (BSII) is a regional approach for assessing cumulative impacts in the Baltic Sea, developed under the Baltic Marine Environment Protection Commission (HELCOM). The most recent geospatial data used for running the BSII analysis represents the years 2011-2016 (HELCOM 2018a). In addition to the output map layers resulting from the BSII analysis, an interactive online Cumulative impact Assessment Tool (BSII CAT; Miloš and Bergström 2019) for running analyses either by using official HELCOM data, using external datasets, or applying targeted analyses of selected data combinations or sensitivity scores is publicly available. The core input to the BSII analysis consists of 18 Baltic-wide pressure layers, each representing the combined pressure from human activities of relevance for the Baltic Sea and identified based on Annex III of the EU

Marine Strategy Framework Directive (EC, 2017) and 42 ecosystem component maps. The input spatial data of the BSII is processed to 1 km raster grid and stems from either regular HELCOM data collection framework or supplemented by data call by national competent authorities. The input datasets are quality assured and commonly accepted by HELCOM contracting parties and are regularly updated during the environmental assessments carried out by the Baltic Sea countries (HELCOM 2010; 2018b). The tool also supports identification of green infrastructure features according to the approach of Ruskule et al. (2019), and cumulative impacts on these (Bergström et al. 2019).

2.2.5. MSP Challenge Simulation Platform

The MSP Challenge Simulation Platform (www.mspchallenge.info) is a multi-user digital platform designed for stakeholder engagement and training in MSP (Abspoel et al., 2019; Steenbeek et al., 2020). An interactive interface enables users to collaboratively develop planning scenarios. By integrating real geodata with science-based simulation models for shipping, energy and ecology, the MSP Challenge simulates the short and long-term effects of plans and their interactions, including possible impacts on the environment (Mayer, et al., 2014). To represent ecological dynamics and food-web feedbacks, the MSP Challenge links to Ecospace, the spatial-temporal module of the free and open source Ecopath with Ecosim (EwE) food web modelling approach (www.ecopath.org; Heymans et al., 2016; Steenbeek et al., 2020). The software was developed by Breda University of Applied Sciences in collaboration with several MSP stakeholders, and funded through the NorthSEE, Baltic LINes and SIMCelt projects.

2.2.6. PlanWise4Blue

PlanWise4Blue is a web-based application developed during the compilation of the Estonian National Maritime Spatial Plan for improved decision-making (2020). PlanWise4Blue combines models of marine economy and cumulative impact assessment. Such a combined model allows one to assess the economic benefits of various management scenarios along with their environmental impact across Estonian sea space. Outcomes of the model make it possible to work towards sustainable solutions to maximize the economic benefit gained from the use of marine resources with minimum damage to the environment. The aim of the economy model is to increase the capacity for knowledge-based management of marine resources and accounting for their potential economic benefits. The aim of the cumulative impact model is to identify various human pressures and account for their cumulative effects on the natural environment, while considering regional differences of nature. The spatial resolution of the model is 1 km^2, and the temporal timescale is 1 year. This tool has been developed to assist with MSP, but is also applicable in other fields, such as environmental conservation and coastal management.

2.3. Analytical framework for MSP-oriented DST evaluation

For analysing the different DSTs, we developed an analytical framework with the aim to provide a comprehensive and objective understanding of the conceptual, technical and practical (in terms planning, management and stakeholder engagement) aspects of the studied DSTs. The framework was designed through a systematic review of existing evaluation frameworks for DSTs in marine and coastal realms (Bolman et al., 2018; Pınarbaşı et al., 2017; Kannen et al., 2016). Compared to existing evaluation studies, this framework is designed and evaluated entirely by the DSTs software developers and DST managers.

The DSTs developers and managers were engaged in this research through an iterative process. The first level of engagement occurred through the workshop on cross-border MSP and environment at the "*ConnectingSeas*" Conference held in Hamburg on 13-14 February 2019 (VASAB, 2019). The workshop introduced the DSTs subject of this study and enabled the necessary knowledge exchange among the developer community and managers through dedicated workstations that showcased the DSTs and their functionalities. The second stage of engagement occurred through two follow-up online meetings with developers focused on identifying objectives of the research and defining the components of the analytical framework (thematic aspects and evaluation criteria) to address the research objectives. A third stage included the compilation by DST developers and managers of the questionnaire that was structured into an *excel* spreadsheet (Microsoft Office 365, 2020) that helped organise responses in a systematic manner. The analytical framework used in this study has the aim: 1) fill existing gaps in the definition of evaluation criteria through the direct participation of the DSTs' developer community into the framework design and criteria evaluation through a vertical integration of technical aspects and DSTs developer knowledge into the design and evaluation of the framework, 2) increase flexibility of DST frameworks in order to ensure application within and outside marine realms (e.g. terrestrial or urban domains) and 3) determine criteria that can be flexibly extended also to specific functionalities linked to the DST, such as for instance cumulative effects assessment, ecosystem services analysis or spatial conflict-synergy analysis.

The analytical framework presented in Figure 2 is based on a three-faceted evaluation approach (Rhee and Rao, 2008). Each facet refers to a specific evaluation category corresponding to conceptual, technical and practical aspects of the DST implementation. The advantage of this approach is that interested parties can narrow down the system evaluation according to the facet. Each aspect is populated with a set of evaluation criteria. The three-faceted aspects are defined below with the addition of a fourth tool-specific facet, namely the Cumulative Effects Assessment (CEA) capabilities. The fourth facet included as the CEA tool is a recurrent instrument in the DSTs and can be compared across the DSTs. We provide below the definitions of the facets (in Annex 1 & 2 an overview of the criteria and respective questions included in the questionnaire is provided):

1. *Conceptual aspects* – Describes the objective, the functionalities of the DST and characterizes its developer and user community.
2. *Technical aspects* – Describes the technical implementation of the DSTs in terms of programming language, framework, data inputs, graphical user interface, API and other services, and the source code availability.
3. *Practical aspects* – Describes the practical outcomes in terms of support to MSP process, application on national and or on pilot study level, link of the functionalities to support decision making.

4. *CEA-capabilities* – Describes the assessment criteria under consideration of the cumulative effects assessments instrument supported by the DST. This includes the CEA definition, CEA model characteristics, key assumptions, means to propagate pressures, pressure-biota interaction application context of the CEA, means to assess and communicate uncertainty.

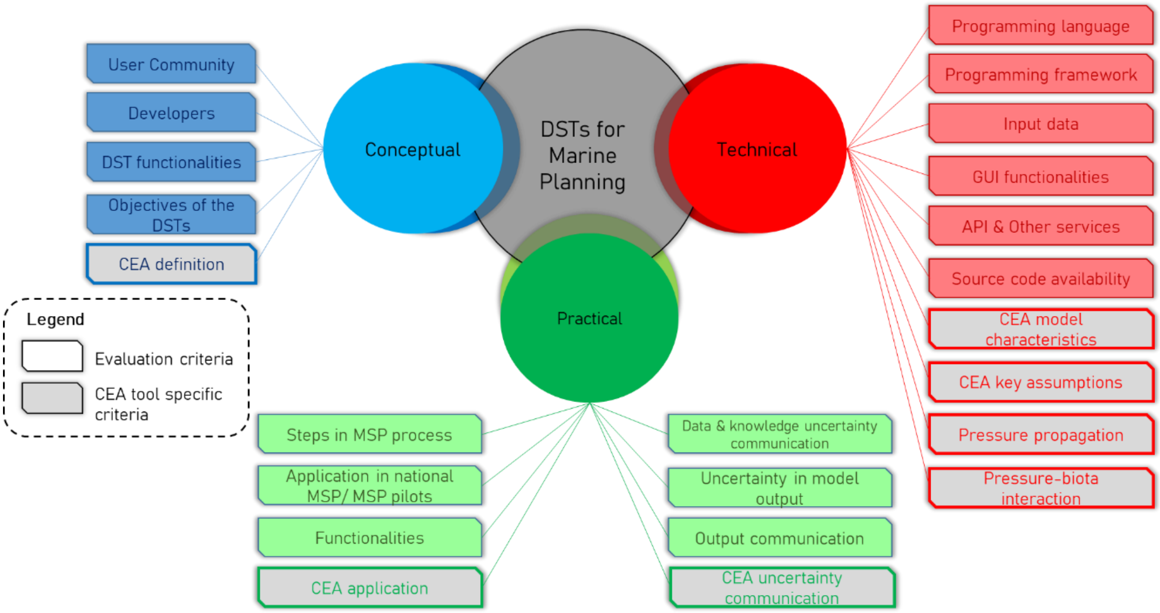


Figure 2. Analytical framework defining the three thematic aspects (Conceptual, Technical and Practical) and the 14 criteria for evaluating the six decision support tools. In grey a dedicated assessment criteria of the cumulative effects assessment instrument is provided. The questions used for the interview were provided in the supplementary material (annex 1 and 2).

2.4. Analysis of responses

The results of the evaluation of the DSTs against the four aspects are investigated through the use of a Sankey diagram based on ggplot2 and ggalluvial library from R programming (CRAN, 2020). In the Sankey diagrams presented in Figure 3 to 5, each DST is represented by a color-code and the links between columns demonstrate the number of elements in DSTs.

Sankey diagrams are particularly useful to visualize the relationship of each DST to each specific criteria (Figure 3 to 5).

3. Results

The following sections present the outcomes of the iterative process of engagement and the subsequent critical evaluation of the questionnaire responses from DST developers and managers. Results were organized into the three thematic aspects (theoretical, technical and practical) as described in section 2.3. In sections 3.5 the analytical framework is applied to analyse the CEA tool capabilities implemented in all the DSTs in terms of characteristics and key assumptions.

3.1. Conceptual aspects

3.1.1. Objectives and functionalities of the DSTs

Figure 3 illustrated the conceptual aspects taken into consideration when developing the DSTs. According to the results of the analytical framework application, DSTs are designed to target multiple-objectives. Among the objectives identified, the most recurrent are: (1) Supporting ecosystem-based management (Mytilus, Tools4MSP, MSP-Challenge, BSII-CAT), (2) contribute to the national MSP process (PlanWise4Blue, BSII CAT); (3) support decision makers in building planning scenarios (Mytilus, MSP-Challenge); (4) increase MSP knowledge through a data platform (Tools4MSP and BSII-CAT) and (5) provide means for CEA analysis (Mytilus, PlanWise4Blue).

The most important functionalities of the DSTs include (1) the implementation of an operational CEA tool (present in all DSTs), (2) addressing spatial conflicts among competing sea uses (Tools4MSP and Mytilus) and the (3) testing of different plan proposals (Symphony and PlanWise4Blue). . Other functionalities include analysis of environmental status and trends (BSII CAT), modelling of ecological impacts of proposed developments through Ecopath with Ecosim (EwE) and increasing awareness and training on maritime spatial planning challenges (MSP Challenge Simulation Platform).

3.1.2. Developers and users of the DSTs

The tools have been developed in a variety of settings with academic institutions as the main developers (Figure 3): MSP Challenge (Breda University of Applied Science), PlanWise4Blue (Estonian Marine Institute, University of Tartu) and Mytilus (Aalborg University, Denmark). The Tools4MSP software was developed by the national research institution, namely the National

Research Council – Institute of Marine Sciences (CNR-ISMAR, Italy). Symphony is the only DST developed by a national planning agency, the Swedish Agency for Water and Marine Management (SwAM). The BSII CAT is developed under an international regional sea convention (HELCOM, Baltic Sea Environment Protection Commission) with support from its contracting parties. In all cases, the main intended users are national and regional planning authorities and decision-makers involved in MSP and other marine environmental management processes. Other users are academic and research institutions, the private sector, NGOs, students and the general public.

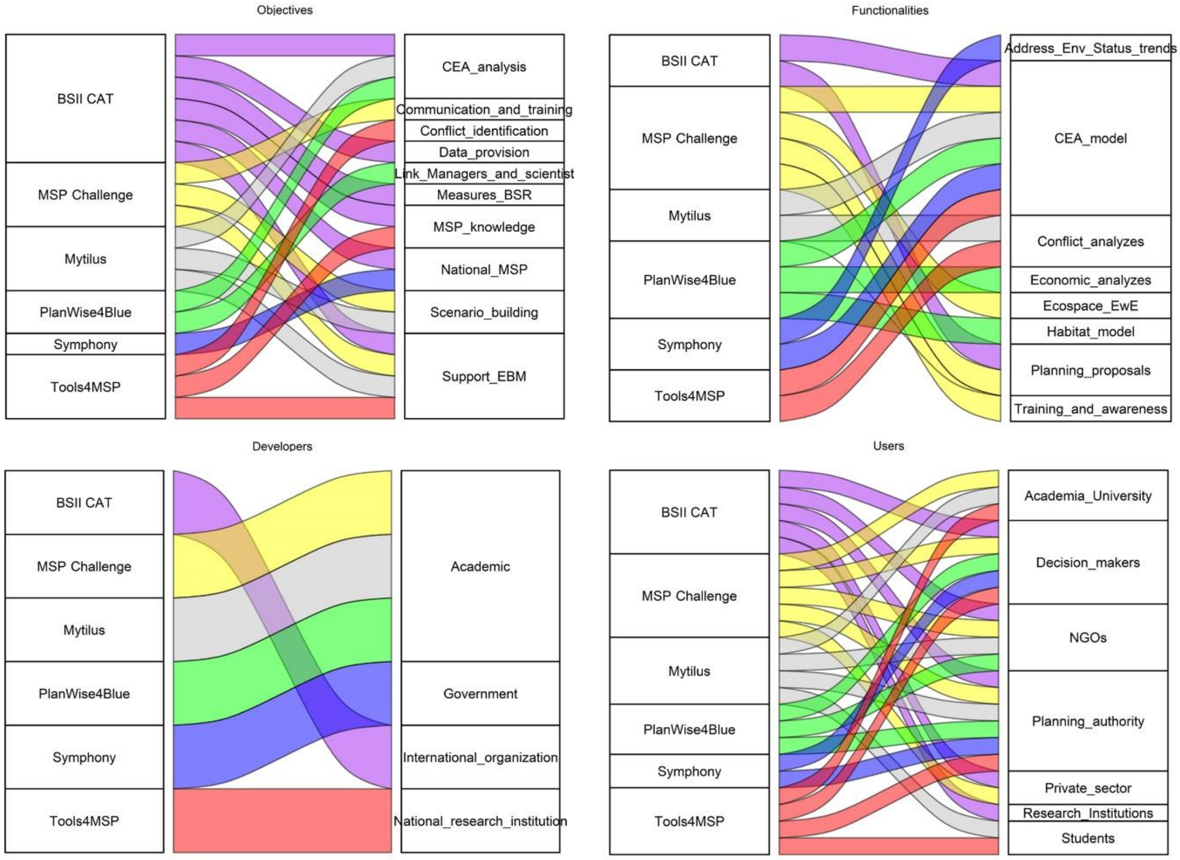


Figure 3. Sankey diagram illustrating the conceptual aspects reviewed in the six DSTs: Objectives, functionalities, developers and users. Note: Objectives – Purpose of the Decision Support Tool within coastal management and MSP; Functionalities – The software processes/services that transform inputs into an output or product (Schmidt, 2013); Developers – Stakeholder in charge of the design, development and technical implementation of the software; User – Stakeholder that uses the software/application/product.

3.3. Technical aspects

An overview of the technical aspects analysed for each DST is presented in Figure 4.

3.3.1. Programming language, software and software framework

Three of the reviewed DSTs are desktop-based (Mytilus, MSP Challenge, BSII), while Tools4MSP, Symphony, PlanWise4Blue and BSII CAT are web-based, and therefore do not require any software installations. The most used programming languages (Figure 4) for DST development are *Python* (Tools4MSP and BSII CAT) and *Javascript* (Planwise4Blue, Symphony). Mytilus is developed in *Delphi 10.1 Integrated Development Environment (IDE)* for high performance calculations. MSP Challenge uses predominantly C#, and Symphony is coded in Java. The different software frameworks used for the DSTs include ArcGIS (BSII CAT), Unity (MSP Challenge), Geonode,(Tools4MSP), Delphi 10.1.IDE (Mytilus) and ASP NET MVC (PlanWise4Blue).

3.3.2. Graphical User Interface functionalities

The Graphical User Interfaces (GUI) provide different functionalities (Figure 4), such as exploration and visualization of geospatial data (all DSTs), up- and downloading of geospatial data, sharing of data and knowledge (MSP Challenge, Tools4MSP and BSII CAT), and the possibility to run geospatial tools and visualize results (PlanWise4Blue, Tools4MSP and Mytilus, BSII CAT). MSP Challenge supports the interactive and collaborative development of spatial plans, and provides access to a knowledge base on the MSP process and the anthropogenic and ecological characteristics of the study region.

3.3.3. Input datasets and source code

Geospatial input data formats for the DSTs include vector and raster layers, while the source of input data depend on the geographic area in focus (Figure 4). For instance, Symphony and PlanWise4Blue use primarily national datasets provided by different authorities and consultants. PlanWise4Blue also has a specific interface that enables users to add experimental and/or survey data in the form of meta-analytical evidence (effect sizes) to the portal. Other DSTs benefit from datasets derived from external data collections, such as EMODnet, ICES or HELCOM. Some of DSTs are also interoperable with WMS/WFS (World Map Services/Web Feature Services) such as Tools4MSP and the BSII CAT (input raster layers can be served as WMS). Source codes of the tools are openly accessible for the majority of DST: Mytilus, Tools4MSP (www.github.com/CNR-ISMAR/tools4msp; www.github.com/GeoNode), EwE - the ecological model (www.ecopath.org/) connected to the MSP Challenge (in progress of becoming open source) and the BSII CAT (https://github.com/helcomsecretariat/Cumulative-impact-Assessment-Toolbox). The availability of an open source code is advantageous since it can stimulate the creation of developer communities around the DST and ensures transparency of the analysis process by providing insights into the code base.

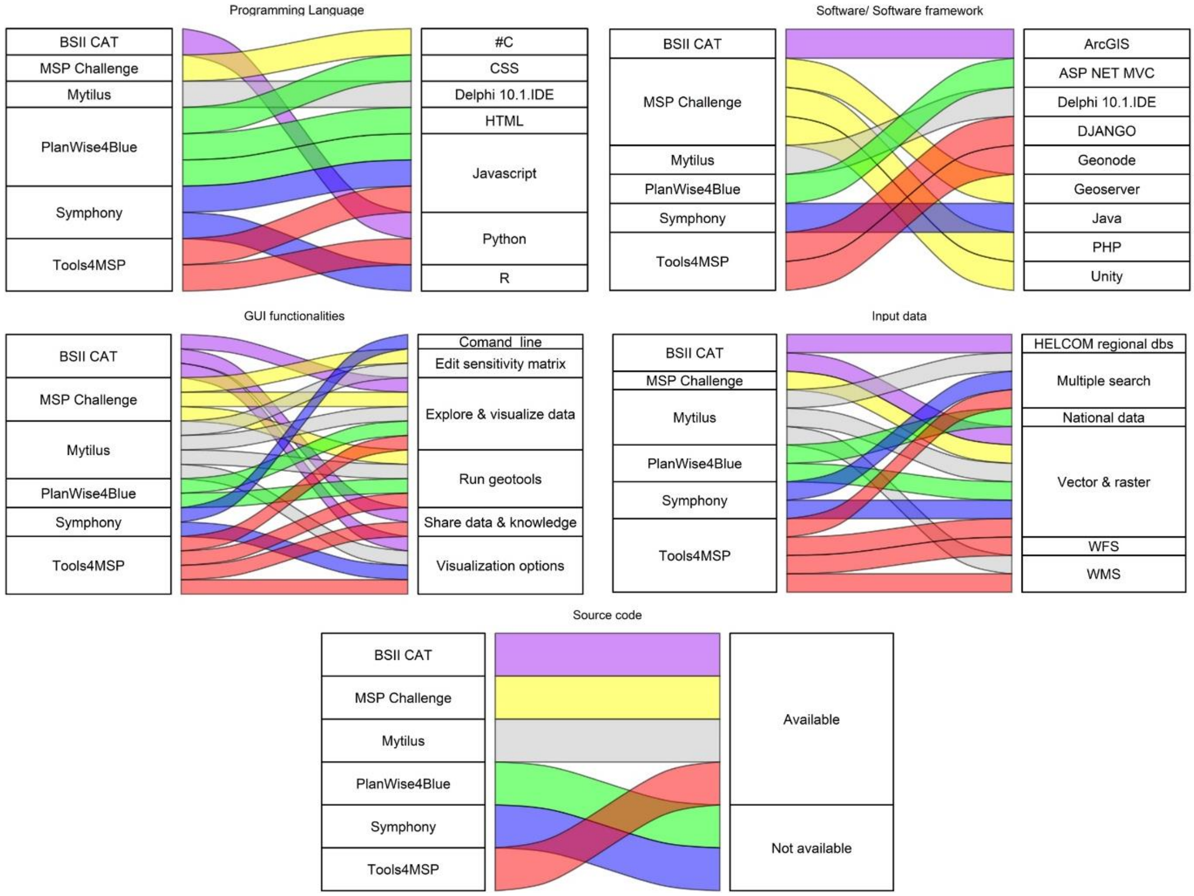


Figure 4 Sankey diagram illustrating the technical aspects reviewed in the six DSTs: programming language, software/software framework, GUI functionalities, input data and source code availability. Note: Programming language – High level language used to write a computer programme (e,g, Python, R, Javascript); Software/Software framework – Operating system used to direct the operations of the computer, including the documentation giving instruction on how to use it; Graphical User Interface functionalities - a software interface designed to standardize and simplify the use of computer programs, as by using a mouse to manipulate text and images on a display screen featuring icons, windows, and menus; Input data - The computer file that contains data that serves as input to a device or program (e.g. shapefile, CSV

raster file); Source code - Code written by a programmer in a high-level language and readable by people but not computers. Source code may be proprietary or open access.

3.4. Practical aspects

An overview of the practical aspects analysed for each DST is presented in Figure 5.

3.4.1. Planning relevance and application domains

In terms of support to MSP, most DSTs focus on the analysis of current conditions and the analysis of future conditions (Figure 5). This corresponds to steps 5 and 6 of the IOC-UNESCO Step-by-Step approach to MSP (Douvere and Ehler, 2009). Mytilus, Tools4MSP, Symphony and MSP Challenge also support stakeholder engagement (step 4). Three DSTs, namely BSII CAT, MSP Challenge and Mytilus were used for stakeholder engagement during pilot MSP testing.

Implementation and validation of actual plans (steps 8 and 9 of the IOC-UNESCO Step-by-Step approach to MSP) depend on formal adoption by national or regional authorities (Ehler and Douvere, 2009). DSTs like Tools4MSP have been applied in MSP pilot studies, such as for the Emilia-Romagna Region in Italy (Barbanti et al., 2018; Farella et al., 2020). Symphony has been used in the development and assessment of the Swedish national MSP by SwAM (Havs- och vattenmyndigheten, 2018, 2019; Hammar et al., 2020). The BSII CAT was recently applied for the assessment of transboundary aspects in Baltic MSP (Bergström et al. 2019); MSP Challenge has been used to engage stakeholders in the North Sea, Baltic Sea, as well as in the Clyde marine area (Scotland); and PlanWise4Blue is currently being used within the Estonian MSP process (Ministry of Finance; Nõmmela et al., 2019).

3.4.2. Stakeholder engagement in DST use and communication of outputs

Stakeholder involvement in the DST use and testing is performed through workshops (Tools4MSP, BSII CAT and Mytilus), educational activities, gaming sessions (MSP Challenge; Figure 5). In the PlanWise4Blue, planners are also directly involved in the development of the DST. Symphony was developed collaboratively by SwAM and the Geological Survey of Sweden, but benefitted from scientific advice from institutions in Denmark, Sweden, and USA at different points. Options regarding visualization and communication of results were revised following the use of Symphony in the national MSP process and the public consultation processes in 2018 and 2019. Outputs of DSTs communicated to stakeholders are mainly in the form of reports (Tools4MSP, Symphony), geodata (Tools4MSP, Symphony), maps and data services (Mytilus, BSII CAT, PlanWise4Blue) and in game discussion and reflection of results (MSP Challenge).

3.4.3. Uncertainty communication

Uncertainty analysis is an essential component to address the inherent complexity of marine ecosystems and their interactions with anthropogenic activities (Carr et al., 2003; Wilson 2017). The majority of the surveyed DSTs (Figure 5) do not provide explicit functionalities to visualize or treat uncertainty. The exception is Symphony, which provides data quality and availability maps, although currently only outside of the tool. The most common strategy to address uncertainty in the DSTs is by reporting uncertainty in data through a dedicated metadata section of the geospatial dataset (Symphony, BSII CAT and Mytilus). For other DSTs, uncertainty is not communicated through the DST nor available at the current stage (PlanWise4Blue).

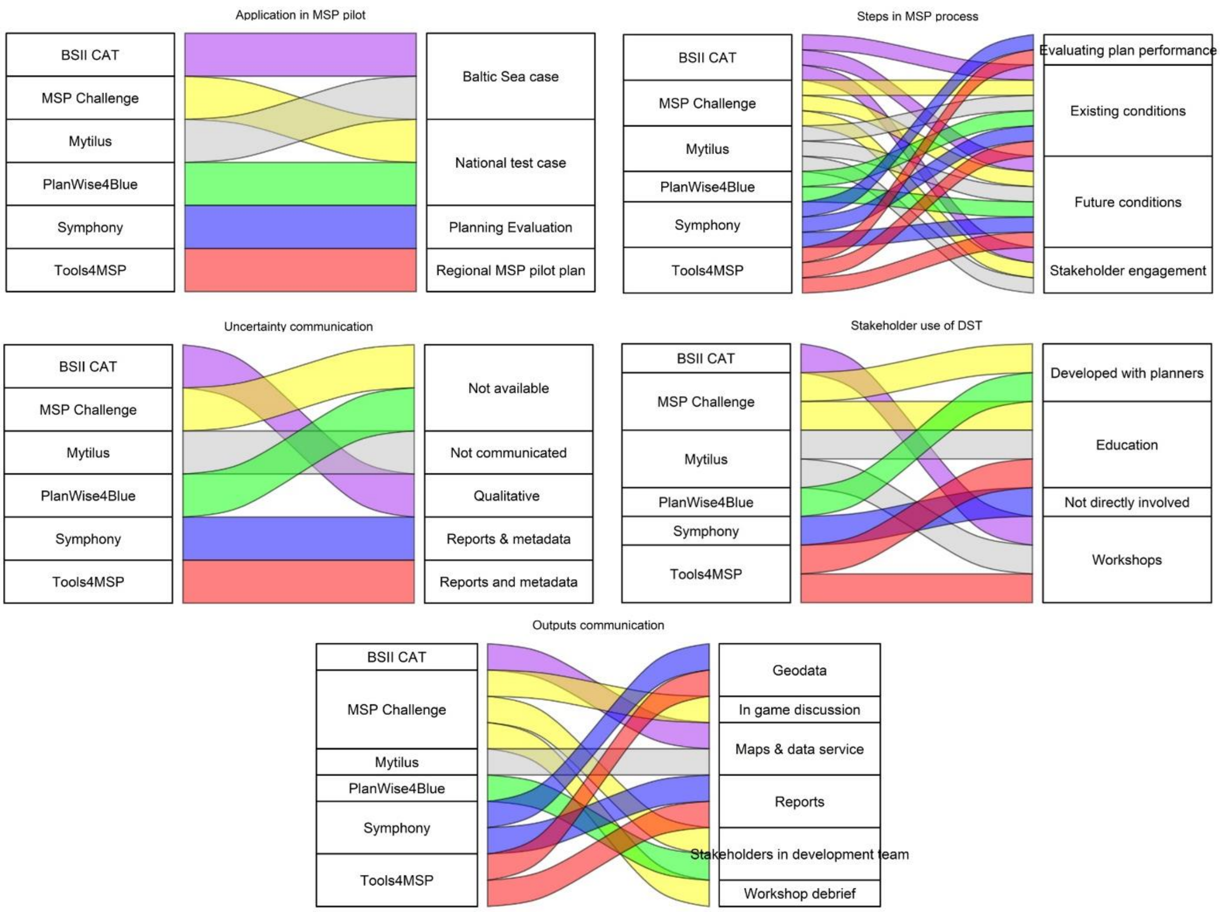


Figure 5. Sankey diagram illustrating the practical aspects reviewed in the six DSTs: Application in MSP pilot, steps in MSP process, uncertainty communication, stakeholder use of DST and outputs communication. Note: Application in MSP pilot – Case study site where the DST has been applied so far and exemplifies its application potential for MSP; Steps in MSP process – MSP implementation steps the DST can be relevant for; Uncertainty communication - ; Stakeholder use of DST – A group of persons that share an interest in applying the software; Outputs communication – Means of communication of the results of the DST.

3.5. CEA implementation within DSTs

3.5.1. CEA definitions, characteristics and key assumptions

All the DSTs implement a CEA model built into their architecture, however with differing definitions. Mytilus provides a CEA definition as follows "*a systematic procedure for identifying and assessing the impacts from multiple activities / pressures on a single or a group of ecosystem components*".

The Tools4MSP modelling framework adopts a definition of CEA based on Judd et al., (2015) as "*systematic procedure for identifying and evaluating the significance of effects from multiple pressures and/or activities on single or multiple receptors*" (Menegon et al., 2018c). Moreover, it uses definitions for "*human activity*", "*uses*" and "*source*" as synonyms and define "pressure" (Judd et al., 2015) as "*an event or agent (biological, chemical, or physical) exerted by the source to elicit an effect*".

BSII adopts the definition of CEA by HELCOM (2018), namely of "*a systematic assessment of the relative distribution of pressures in the Baltic Sea and of their combined (additive) impacts on environmental components, considering pressures prevailing in the Baltic Sea during the assessed time period*". The definition was reassessed in the Pan Baltic Scope project, suggesting to develop the regional CEA (BSII) to become more operational in MSP ("*Impacts on the environment that result from several human activities and pressures acting together, as caused by past, present or any possible foreseeable actions within the project or work task to solve*" (Bergström et al, 2019). In PlanWise4Blue, CEA is described as the quantification of "*synergistic cumulative effects that are defined as interactions between two or more effects, when the resultant combination is greater or different than the simple addition of the effects*."

In the MSP Challenge, a simplified CEA model is used in response to the major challenge of combining a wide range of human activities with a simplified pressure-response system necessary for fast system response (Steenbeek et al., 2020). In MSP Challenge impacts on ecology are modelled using Ecospace niche model, (restrictions to) fishing, food web dynamics, and optionally, environmental change. At the current stage, Symphony has not yet adopted any specific definition for its CEA tools, but the tool employs the approach and impact estimation method developed by Halpern et al. (2008).

CEA model characteristics and key assumptions of the DSTs are summarised in Table 2. The DSTs' CEA applications showcase different characteristics. For instance, Symphony and Mytilus provide scenario-comparison functionalities to compare the effects of different spatial planning strategies; the PlanWise4Blue determines impacts on environmental component in terms of lost nature assets as in terms of surface area. In the Tools4MSP the pressure distance model functionalities can accommodate different pressure propagation, such as for instance hydrodynamic models to address eutrophication effects from terrestrial N and P loads.

Key assumptions on CEA implementation concern mainly the pressure propagation models, which mimic equal pressure dispersion in all directions for Tools4MSP, Symphony, BSII CAT, MSP Challenge and PlanWise4Blue. The majority of DSTs lack indirect pressure-effects interaction modes, with exception of MSP Challenge, which considers predator-prey relationships explicitly and dynamically. In addition, in the current CEA implementation of the DSTs, synergetic and antagonistic interactions are to a great extent not addressed. Another key assumption and potential limitation in some uses of CEA is that effects on marine ecosystems are modelled without taking into consideration the spatio-temporal variability of the impact chain components, namely pressures and environmental components. However, the MSP Challenge supports dynamic changes of the impact chain components simulated over time.

Table 2. CEA model characteristics and key assumptions according DST experts and users. Note: CEA – Cumulative Effects Assessment, DST – Decision Support Tool.

DSTs	**CEA model characteristics**	**Key assumptions**
Mytilus	(1) Weighted score of use-pressure (2) Linear ecosystem response to pressure (3) Sensitivity matrices are customized for each plan area	(1) All pressure layers and ecosystem components are considered equally (2) Pressures are propagated in all directions equally (3) Pressure-effect interaction do not consider synergistic/ antagonistic interactions (4) Pressure-effect interaction do not consider indirect effects (e.g. predator-prey relationships) (5) Currently the temporal dimension is not considered
Tools4MSP	(1) Weighted score of use-pressure (2) Non-linear to S-shaped ecosystem response to pressure (3) Flexible distance model that can accommodate different pressure propagation models (4) Additive and dominant pressure-effect interactions (5) Sensitivity matrices are customized for each study area	(1) Pressures are propagated in all directions equally (2) Pressure -effect interaction do not consider synergistic/ antagonistic interactions (3) Pressure-effect interaction do not consider indirect effects (e.g. predator-prey relationships) (4) Currently the temporal dimension is not considered
Symphony	(1) Sensitivity matrices are customized for each plan area (2) Ecosystem and pressure models are custom made - data modelling is not part of the DST (3) Scenario function, with tool to visualize differences under different MSP policy scenarios	(1) Pressure-effect interaction do not consider synergistic/ antagonistic interactions (2) Pressure-effect interaction *do not* consider indirect effects (e.g. predator-prey relationships) (3) Currently, the temporal dimension is not considered (the latest version of Symphony use data for the period 2012-2016)
BSII CAT	(1): Default pressure layers are customized either based on weighted scores of use-pressure and the estimated propagation from human activities, or on direct data/model results of pressures at sea (2) Generic sensitivity matrix for the whole Baltic Sea available and modifiable by user	(1) All pressure layers and ecosystem components are considered equally by default. Option available to select other combinations and to aggregate ecosystem components hierarchically (2) Pressure-effect interaction do not consider synergistic/ antagonistic interactions (3) Pressure-effect interaction models *do not* explicitly consider indirect effects (e.g. predator-prey relationships) (4) Temporal dimensions not considered outside of what the

		selected input data represents, possibility to use own data
PlanWise4Blue	(1) The standardized effect-sizes are calculated based on empirically driven functions. (2) Separate and interactive effects between pressures and the biota are allowed. (3) Effects are calculated in terms of nature assets lost (mostly in terms of surface area)	(1) All pressure layers and ecosystem components are considered equally (2) Pressures are propagated in all directions equally (3) Pressure-effect interaction do not consider indirect effects (e.g. predator-prey relationships) (4) Currently the temporal dimension is not considered
MSP Challenge	1) Weighted score of use-pressure to maintain coherence throughout the system (2) Action - pressure conversion is optimized for short simulation model runs during live game play, and is therefore simpler than Halpern et al (2008) outline (3) Sensitivity matrices are customized for each plan area (4) Pressures impact ecology through the Ecospace niche model, (restrictions to) fishing, food web dynamics, and optionally, environmental change	(1) Pressures are propagated in all directions equally (2) Indirect pressure effects are considered through predator-prey relationships. (3) Simulations support dynamic changes of the impact chain over time.

3.5.2. CEA input data

Input data used for CEA modelling are retrieved from multiple sources (Figure 6). Mytilus and the BSII CAT are supported by the HELCOM Data collection framework by utilizing the datasets made available from HELCOM Map and Data service (data adapted to regional scale and BSII input format with raster 1 km raster resolution) based on sources as described in each metadata sheet. Tools4MSP derives spatial layers for the Adriatic-Ionian Region from EU portals (EMODnet), national/regional datasets (especially Emilia-Romagna and Veneto region) and information generated from projects (e.g. SHAPE and MEDPAN). In PlanWise4Blue, datasets are defined and provided by national authorities, while MSP Challenge uses a variety of datasets according to the region for which it is developed (e.g. HELCOM for the Baltic Sea edition, EMODnet for the North Sea edition, but also in combination with national and other data sets), that are simplified for system optimization while building the edition (region specific) of the platform. Symphony has used datasets from multiple sources, including regional data from EMODnet and ICES but primarily from national data archives.

3.5.3. Pressure definitions, land-sea interaction, pressure propagations and pressure-environment interaction

Figure 6 presents a summary of the anthropogenic pressure definitions adopted, the pressure propagation applied, land-sea interaction (LSI) sources and pressure-biota interactions implemented.

In the CEA regime of terms a pressure can be defined as "*an event or agent (biological, chemical, or physical) exerted by the source to elicit an effect*" (Judd et al., 2015). The categorisation of anthropogenic pressures in the CEA instrument of DSTs were commonly derived from the MSFD Annex III (EC, 2017) for the Mytilus, Tools4MSP Modelling Framework and BSII CAT (including human activities that are of relevance for the Baltic Sea), while other CEAs (Symphony, PlanWise4Blue and MSP Challenge) use more customised pressure setups or a selected list of pressures adopted to specific geographic conditions and planning objectives. Expert-based knowledge is a commonly established approach to identify the areas of influence for pressure (distance propagation) and determine the sensitivity scores in all the DSTs presented.

The term Land-Sea Interaction (LSI) describes the impact of both natural processes and human activities on the coastal ocean. In MSP it is essential to consider the dynamics that occur between land and sea, thus ensuring it is conducted in an integrated manner across maritime and terrestrial areas (EU, 2017).

Incorporating land-based pollution and spatio-temporal dynamics remains a major challenge within CEA modelling, requiring sophisticated hydrodynamic models and particle behaviour modelling.

For instance, the Tools4MSP modelling framework considers river outputs and coastal urban areas through the integration of geospatial outputs from hydrodynamic model for nitrogen, phosphorous and organic matter (Menegon et al., 2018a and c; Depellegrin et al., 2017). The BSII CAT and Symphony incorporates land-based pollution directly into pressure layers representing measures levels at sea. Land-based phenomena are not yet taken into consideration in PlanWise4Blue and MSP Challenge.

The spatial modelling techniques for pressure propagation mainly use spatial buffer operations. Buffering is the process of creating one or more zones around selected features, within a pre-specified distance, usually defined as Euclidean distance (spatialanalysisonline, 2021). The distance around features, such as oil & gas platform, a shipping lane or an offshore wind farm were usually defined through expert knowledge and literature review.

In terms of pressure – biota interaction, that can be defined as the effects of one or more pressures over the environmental receptors (e.g. marine mammals or habitats), all DSTs analysed take into consideration the additive effects, resulting from the sum of the individual pressures on the biota. Dominant interactions are taken into considerations by Mytilus, BSII CAT and Tools4MSP. More specific interaction modes are incorporated into some of the tools, such as mean scores (Mytilus), synergetic effects (PlanWise4Blue), where the combined effect is larger than the additive effect of each individual pressure, and multiplicative pressures interactions (MSP Challenge), where the relationship between the pressures changes, as their values/intensities changes and the overall effect can vary from antagonistic to synergistic.

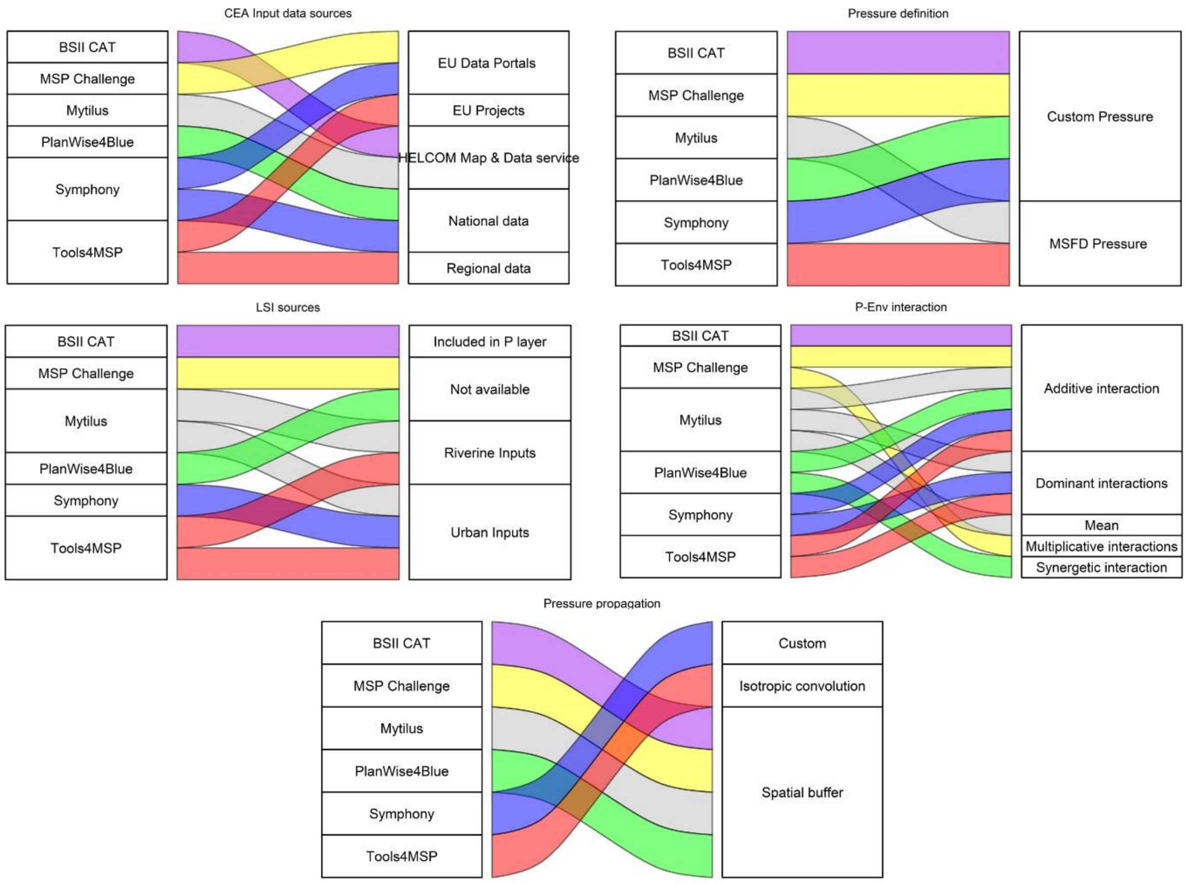


Figure 6. Sankey diagram illustrating the CEA capabilities reviewed in the six DSTs: CEA input data, pressure definition, Land-Sea Interaction (LSI) sources, Pressure-Environment (P-Env) interaction and pressure propagation.

4. Discussion

The analytical framework used in this research for the comparative assessment of DSTs for MSP is adequate and sufficiently flexible for evaluating the key conceptual, technical and practical dimensions of the selected DSTs. The framework can also be applied within a wider marine environmental domain and in particular for the analysis of tools that support single sectors of the Blue Economy such as ocean energy or aquaculture suitability analyses (Bricker et al., 2016; Gimpel et al., 2019) and even instruments dedicated to terrestrial planning (e.g. ARIES; InVEST). A precondition for the use of analytical framework is the need for a range of expert knowledge that goes beyond the planning knowledge and that therefore includes software developers in the evaluation, that are expert profiles dedicated to the architecture and design of a DST.

Compared to other frameworks in the context of marine management, the presented framework has the advantage of having been designed entirely by developers and managers of the DSTs. This stands in contrast to other frameworks developed so far for coastal management and MSP (e.g. Bolman et al., 2018; Janßen et al., 2019), where survey based techniques and/or desk research were applied to investigate instruments capabilities across different stakeholder groups (e.g. researchers, decision-makers, practitioners, etc…). In this study, the engagement with developers and DST managers provided a higher level of insights into the technical development of the DST, the peculiarities of the CEA tool offered by the DSTs (Table 3) and a set of recommendations (see section 4) for the further development of DSTs.

The framework allows the investigation of different aspects of stakeholder involvement related to the design and use of the DSTs, as well as to the applicability of DSTs in different stages of MSP processes, with particular focus on stages involving stakeholder engagement. Results of our research show that in the majority of cases, planners are involved in the development of DSTs as they address planning constrains within their daily working activities. Stakeholders have also been involved through workshops. In this sense, the framework highlighted that stakeholder engagement processes that aim at contributing to the design of DSTs are less common in MSP processes or are usually restricted to collaboration mechanisms internal to the DST development team. In fact, the framework was shown to be effective in highlighting this aspect and could help to further share experience with the authorities responsible for DST, as well as for sharing best practices on stakeholder-and sector-focused development of DSTs. Although the framework was tested on a set of instruments with different stages of development, further integrations of other DSTs can help to improve the framework's criteria with focus on MSP and coastal management. Furthermore, the framework could benefit from a comprehensive stakeholder engagement of decision-makers, maritime sector representatives, and developers to facilitate a co-creation of knowledge and functionalities within DSTs.

The modelling approaches used within the CEA analysis show two main criticalities:

First, the techniques to model land-sea interaction processes, such as the dispersion of riverine inputs (for example nutrients like N and P) or pollutants (e.g. heavy metals, pharmaceuticals) were applied using different modelling approaches. The simulation of riverine inputs requires additional modelling capabilities, ideally through the application of hydro-dynamic models, such as SHYFEM (Shallow water HYdrodynamic Finite Element Model; De Pascalis et al., 2016) or HYPE (Hydrological Predictions for the Environment; Arhemier et al., 2012) that are not always available and that require extensive modelling capabilities and data processing. In the examples studied, the coupling of ecological models, such as Ecopath with Ecosim and Ecospace is exclusive to the MSP Challenge. None of the other DSTs currently has such functionality. One major difficulty in the implementation of ecological models is the extended modelling capabilities and performances required, often related to additional data requirements (e.g. functional groups) Such models are specific for the bio-geographic area to be investigated, which creates further challenges(Steenbeek et al., 2020).

The propagation of pressures takes into consideration various approaches, including a spatial buffer (e.g. PlanWise4Blue), an isotropic convolution function (Tools4MSP) or other customized approaches (e.g. BSII CAT) Further research and collaborations are required to identify standard procedures to take into account pressure propagations that can be applied in the absence of dynamic models. This would facilitate comparison of results among different sea areas, which is particularly important in transboundary planning contexts.

The DSTs also demonstrate different approaches to categorising environmental pressure. Some were customized to better adapt local or macro-regional environmental impacts and planning needs (e.g. PlanWise4Blue, Symphony, BSII CAT), while others apply standardized pressure categories, such as MSFD (Marine Strategy Framework Directive) pressures (Tools4MSP and Mytilus). To facilitate comparison among DST, results should enable a cross-reference between custom and MSFD pressures.

While not directly implemented into the analysed DSTs, there is an increasing segment of literature illustrating the need for uncertainty analysis in expert knowledge, data and modelling in CEA (Jones et al., 2018). DSTs, such as Tools4MSP address knowledge gaps in expert-based sensitivity score and buffer distance were using quasi-Monte Carlo Method (Menegon et al., 2018c). Symphony uses a three-level quality estimation (excellent, good, bad) for each pressure based on a subjective interpretation by the dataset creator along with a descriptive assessment of data limitations (metadata). The spatial interpretation is aggregated into a map of data quality and a map of data availability. The BSII CAT is accompanied by a descriptive assessment of uncertainties in data and sensitivity scores (HELCOM 2018b).

The diverse functionalities of the DST can be partially explained by the different MSP objectives.

Mytilus was developed in order to provide maritime spatial planners with a user-friendly tool, which could support the ongoing maritime spatial planning processes. Although, Mytilus is primarily developed in a Baltic Sea context, it is independent of location and scale and can thereby be applied from regional to local scale all over the world. Among the central features, Mytilus applies a scenario-based approach to facilitate a comparison of the effects on the marine environment from various plan proposals. In addition to the cumulative on the environment, Mytilus can also assess the potential conflicts and synergies from new maritime activities. Furthermore, the rapid calculation speed of

Mytilus supports the active involvement of stakeholders by making the different calculations and map-based scenarios visible immediately.

The Tools4MSP modelling framework was developed to provide a data repository and modelling instrument for MSP in the Adriatic-Ionian Region and to support the implementation of two key pillars of the European Strategy for the Adriatic-Ionian Region (EUSAIR), namely Blue Growth and environmental protection (EUSAIR, 2020). The CEA tool provided by the Tools4MSP modelling framework was applied also within offshore renewable energy developed in the North Sea (Gusatu et al., 2020) and within the ecosystem services threat analysis (Depellegrin et al., 2020). Among the central features of Tools4MSP is its community-based approach, where multiple data on environmental features and maritime activities are collected into the Tools4MSP geoportal by various regional authorities and EU-wide data repositories (e.g. EMODnet).

In Symphony the key functionalities are determined by the key intended purpose of the tool in support of the Swedish national MSP. This is to make visible the spatial distribution of key environmental values and human pressures, and, based on these, an estimation of the severity of impacts associated with the activities that MSP can regulate. For planners, and for those conducting the SEA of the plan proposals, the key advantage of the tool is that it congregates and makes visible in one single instrument/tool information that would otherwise be spread out over many different sources. It does so by means of a spatial representation, which again is a key functionality required for MSP. The only thing limiting Symphony's applicability to other regions than the Baltic is the data sets. At present work is ongoing within SwAM's international cooperaton programme to develop a version of Symphony for the Western Indian Ocean – something that shows the tools versatility, provided that data is available in a format that is usable by the tool.

The BSII supports transboundary MSP in the Baltic Sea (e.g. Bergström et al. 2019), but was originally developed for environmental assessment, that is, to identify prioritized pressures and geographic areas for environmental management actions (e.g. HELCOM 2018). Hence, the tool is developed to be coherent with pressures, ecosystem components and assessment periods as defined by the MSFD (EU 2017) and the Baltic Sea Action Plan (HELCOM 2007). There is a continued need to further develop spatial data and sensitivity matrices to improve the accuracy and relevance of the provided assessments, and additional modules could preferably be incorporated to assess e.g. impacts on ecosystem services, further enhancing its utility in MSP (Bergström et al. 2019, Ruskule et al. 2019).

The PlanWise4Blue instrument was developed to address a set of limitations in CEA tool development and application. The majority of marine areas are impacted by multiple concurrent stressors, which rarely act in isolation but instead produce interactive effects on multiple nature values (e.g. Stockbridge et al., 2020). Surprisingly, the most of cumulative impact tools are still limited to a simplified pressure-response system (i.e. single pressure on single or multiple nature assets) (e.g. Krueger and Schouten-de Groot, 2011; HaV, 2018; HELCOM, 2018) as well as they only rarely use empirical data to define response functions. These limitations render the guidance of ecosystem-based allocation of human activities at sea highly biased, thereby undermining any assurance that societal environmental and socio-economic sustainability objectives will be achieved. This is also very relevant in the MSP context where planners often seek for the best combinations of co-uses in different seascapes; however, if antagonistic/synergistic effects on ecosystems cannot be evaluated, the sustainable planning solution cannot be reached. The PlanWise4Blue tool incorporates the majority of regional scientific evidence in a way that its algorithm is capable of quantifying both single and synergistic effects of most important human activities on a broad range of nature assets. Nevertheless, the important challenge remains as the CEA tool need a regular updating of the input data, i.e. nature data layers and information concerning impacts, and refinement to the model algorithms. Such research should be carried out in a collaborative manner resulting into more harmonized and efficient tools characterized with enhanced predictive capacity and a reduction in uncertainty. As the effectiveness of CEA to provide robust information centres on the use of scientific knowledge and data on different nature assets and specific pressure effects, adoption of observational and experimental evidence into the CEA framework should be encouraged. However, many aspects lack both knowledge and data. But even then, the CEA tools can be used to inform managers of the current gaps in knowledge in order to address these limitations more effectively. Through such principles the CEA tools allows knowledge from empirical marine science to be applied effectively in decision-making, bridge the divide between science and management and support sustainable development.

The MSP Challenge was designed mainly for stakeholder engagement and education, those goals shaped the platform in a great way in terms of scale and depth of information as well as the functions available. For example, the gaming nature of the platform allows and fosters interaction between stakeholders through open discussion, focusing on problem-solving under time and information constraints. On the other hand the platform was designed to be scalable to any region of the world, proof that this has been achieved is the fact that there are already 3 editions of the platform (North Sea, Baltic Sea and Clyde Marine Region). The platform uses data and information at a sea basin scale and was designed to provide feedback to non-technical stakeholders, as a cross-sector planning tool. Different stakeholders from different sectors need to be able to interpret the results in the platform and understand the potential effects that their plans may have on other sectors. The incorporation of the ecospace modelling tool (EwE) requires the customization of the region's EwE model for MSP Challenge purposes and the pressures that influence this model are adapted taking into account the scale or the region and ecospace cell size for the region. Differences in the implementation of the underlying EwE model between study systems will propagate differences in responses, as local and regional effects are captured in different ways across spatial scales (Steenbeek et al., 2020).

4. Recommendations

Based on the presented analysis we propose a set of recommendations to advance DST development to better align their functionalities with ongoing MSP needs and further stimulate knowledge and experience exchange among the actors at the forefront of the DSTs development:

- *Coordinated actions*. Enforce coordinated actions aiming at exchanging experiences among practitioners and the scientific community on the DST development progress, not only nationally or within a sea basin, but also across macro-regions, to sustain knowledge transfer in different stages of CEA and MSP implementation and support comparative analyses. Identify enabling factors, tool development solutions and best practices that can be transferred to appropriate fora and decision-making levels.
- *Community of practice on DSTs for MSP*. Establish expert panels dedicated to sharing knowledge and experience on the conceptual, technical as well as planning and management aspects of the DST with the aim to identify needs and ensure mechanisms to address them. The results of this study suggest five focal areas for such communities of practice: (1) CEA impact chain and its components (including accounting of land-sea interactions and pressure-biota relationships), (2) estimating and communicating uncertainty, (3) DSTs and data infrastructure, (4) further implications for socio-economics and blue growth, and (5) strengthening the capacity of stakeholders relative to DSTs.
- *Open data and data sharing*. MSP is a data-intensive public decision-making process. At the regional level, establish and maintain regular data (e.g. annual) collection routines and when necessary, supplement with "*data calls*", as applied e.g. by HELCOM (2018) to ensure systematic harmonization, collection and sharing of data, methodological approaches and modelled data products from national contact points, which are coherent across different assessment scales (e.g. data resolution, modelling procedure and indicators).
- *Remote sensing*. Develop and apply remote sensing techniques that enhance the monitoring and the assessment of human-marine environment interaction and provide diverse application opportunities in the MSP realm. While none of the DSTs deploys remote sensing techniques directly into their functionalities, their potential contribution to MSP is manifold, encompassing for example the definition of biogeographic regions, mapping of ecosystem elements, assessing intensities of maritime traffic or detection of pollution.

- *Terminology*. In order to ensure a coherent CEA framework, develop and adopt a unified glossary on central concepts and aspects. A potential starting point is to address CEA at strategic planning level of MSP as the basis for a harmonization process.
- *Data standards*: Utilise existing and further develop data sampling designs collection and archiving guidelines and standards for scale-specific CEA models (including for example preferred format, attribution and quality) and provide guidance on how to gather and archive data for CEA. Also, develop mechanisms to incorporate source data updates (semi-) automatically from well-managed and standardized web archives so that models of pressures and ecosystem components are based on common sources and the CEA process is facilitated through collaborative and standardized transboundary information management projects.
- *Handling uncertainty*. Develop models and define guidelines for estimating uncertainty in data, knowledge and modelling, including means for visualizing uncertainties in CEA outcomes using GIS and simulation algorithms.
- *Evidence based*. Increase the scientific knowledge-base on the effects of anthropogenic activities on biodiversity at different scales in order to reduce uncertainty in scoring within sensitivity analysis and pressure propagation models. Define transparent means to incorporate information from diverse sources of knowledge, and to integrate information on associated uncertainty into MSP supporting DSTs.
- *Artificial Intelligence*. Artificial intelligence techniques such as machine learning (ML) are getting increased application in GIS as predictive modelling of commercially valuable fish species, iconic species such as marine mammals for conservation purposes and in sectorial domains, such as aquaculture suitability analysis and shipping traffic regulation. DSTs can take advantage from existing data platforms (e.g. DATRAS) for dynamic incorporation of ML-based spatial data into planning and CEA.
- *Support integration of socio-ecological and economic analysis*. In order to broaden the support to MSP processes, further extend the capabilities of the DSTs in the handling and

processing of socio-economic and socio-ecological knowledge. This allows widening the scope of the DST towards blue growth applications, incorporation of economic values into strategic analyses and addressing the contribution of natural assets and implications of impacts on these for human well-being.

5. Conclusions

The presented research provides a detailed overview of the conceptual, technical and practical aspects of six DSTs that can support national and transboundary MSP at different geospatial scales. The analytical framework that was developed through the engagement of developers and managers of the DSTs resulted to be an effective instrument to identity, address and compare key aspects in the different DSTs. The framework can be used as diagnostic instrument to analyse the usefulness of the DST and therefore contribute to knowledge sharing and experience exchange among actors involved in the development and application of the DST for MSP and coastal management. A further extension of the framework should include more DSTs that may include as well other tools, such as conflict-synergy analysis, displacement of marine uses or instruments for ecosystem-based management of marine resources. This would increase the assessment capacity of the framework and widen stakeholder involvement in the analysis to better incorporate user experience and needs into the DST design.

The lack of a common terminology and criteria for CEA, lack of evidence at a large scale of the effects of human actions on the marine ecosystem, combined with the only recent sharing of data and the lack of coordinated actions in the sector are currently the greatest obstacles for better DST development. Regional cross-comparison between DSTs can identify the existing weaknesses of individual tools, and identify possible complementarity between tools, facilitating goal-oriented applications of individual or combined DSTs for local, national and regional specific utilisations. Last, the confidence DST output can be improved by adopting an ensemble approach to MSP, where the results of multiple DSTs – each with their unique representation of processes, internal assumptions, and unavoidable strengths and weaknesses – are applied to the same planning scenarios.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The Tools4MSP Modelling Framework was partly financed by the PORTODIMARE Project (Adriatic-Ionian Programme – ADRION). Symphony contribution was part financed by FORMAS through the ClimeMarine project. JK was financed by the Estonia-Russia Cross Border Cooperation Programme project "Adrienne", the RITA1/02-60 project "Innovative approaches to monitoring and assessing marine environment and nature values in Estonian sea area" and the BONUS MARES project funded by the European Union's Seventh Framework Program for research, technological development and demonstration though BONUS, the joint Baltic Sea research and development Program (Art 185). MSP Challenge Simulation Platform was developed by Breda University of Applied Sciences co-funded through the NorthSEE project (2016-2019), (Interreg North Sea Region program of the EU-RDF), the Baltic LINes project (2016-2019), (Interreg Baltic Sea Region program of the EU-RDF); The Scottish Government, Marine Scotland and the Scottish Coastal Forum through SIMCelt (EU Directorate General for Maritime Affairs and Fisheries) (2015-2018). The design and development of MEL was funded by the Ministry of Infrastructure and Water Management / Rijkswaterstaat, the Netherlands; further thanks to everyone involved in the different projects (https://community.mspchallenge.info/wiki/Credits). Recent developments in the BSII CAT were enabled through the EU Pan Baltic Scope project, co-funded by the European Maritime and Fisheries Fund of the European Union. The development of Mytilus has been supported by the project 'BONUS BASMATI – Baltic Sea Spatial Planning for sustainable Ecosystem Services' (2017-2020), which has received funding from BONUS (Art. 185), jointly funded by the European Union, Innovation Fund Denmark, Swedish Research Council Formas, Academy of Finland, Latvian Ministry of Education and Science, and Forschungszentrum Jülich GmbH, Germany, as well as from the NorthSEE project (2016-2019), which has received funding from Interreg North Sea Region program of the EU-RDF,

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Supplementary material

Annex 1. Structured questionnaire applied for the analysis of Decision Support Tools.

Thematic aspects		Evaluation Criteria	Question
Conceptual		Objective of DST	1. *What are the main objectives of the DST?*
		Purpose of the DST	2. *What is/are the purposes of the DST?*
		Developer	3. *Who is in charge for the development and maintenance of the DST?*
			4. *Type of institution?*
			5. *Is the developer also the main problem-owner?*
		Other institutions/organizations/agencies involved	6. *Other institutions /organizations/authorities are collaborating in the development of the DST?*
		Target groups	7. *Who are the target groups of the DST*
		Supportability of the DST	8. *What EU/national /regional/private project funding received the DST?*
			9. *To what extent is or will the DST be supported/sustained in the future?*
			10. *What is the strategy for the long term sustainability of the DST after its project life time?*
		Geospatial tools	11. *What geospatial models can be used through the DST?*
Technical		Application Type	1. *What type of application is the DST?*
		Software	2. *What are the programming languages the DST is based on?*
			3. *What is the software framework?*
			4. *What software is the DST based?*
		Graphical User Interface (GUI)	5. *Does the DST have a graphical interface* 6. *What are the main functionalities of GUI?*
		Documentation & Guidelines	7. *Does the DST provide documentation and guidelines for its usage?*
			8. *List resources of information*
		Community	9. *Does or will the software have and active user community?*
			10. *Does or will the software have an active developer community?*
		Portability	11. *On what platforms does it work (Windosws, Linux McIntosh, etc...)*
			12. *On what browsers does the DST work (Chrome, Firefox, Explorer, etc...)*
		Input data & flows	13. *Type of input data*
			14. *Sources of input data*
			15. *Accessibility of input data*
		Geographic domain	16. *In what geographic domains was the DST originally applied?*
			17. *In which other regions outside its geographic domain was the DST and/or its tools applied?*
			18. *Provide some reference information*
		Interoperability	19. *Is the DST interoperable with other services or API?*
			20. *What services and API is currently integrated in the DST?*
		License	21. *What software license is adapted to the DST?*
			22. *Is the source code accessible*
			23. *Provide a link to the source code*
		Outputs	24. *Type of output data*
			25. *Accessibility of output data*
Practical	(PM) Planning & Managment utilization	DST-MSP Process	1. *What stages of an MSP process can DST be used?*
		Application of the DST in national MSP process or MSP pilot site	2. *Is/will the DST be introduced into national/regional MSP process?*
			3. *Provide some reference information*
			4. *What are the enabling factors for introducing the DST into the MSP process?*
			5. *How will the DST contribute to the national/regional MSP process?*
		Reliance of the DST	6. *How is the uncertainty in knowledge communicated in the DST?*
			7. *How is the uncertainty in data communicated in the DST?*
			8. *How is the uncertainty in model results communicated in the DST*
	(DSN) DST-Stakeholder nexus	Level of inclusion of stakeholders	9. *How are stakeholders involved in the DST use and testing?*
		Visualization & Effectiveness	10. *How are outputs communicated to stakeholders?*

Annex 2. Cumulative Effects Assessment questions

Criteria	**Question**
CEA definition	*1. How is a CEA defined within the DST?*
CEA algorithm	*2. How does the CEA algorithm differ from Halpern et al., 2008?*
Impact Chain	*3. Does the CEA include all three components of an impact chain (human activities-pressures-environmental components)*
Sensitivity scores	*4. How are sensitivity scores provided?*
	5. How can the user modify sensitivity scores within the CEA
Input data sources	*6. How are geospatial datasets on human activities retrieved/modelled?*
	7. How are geospatial datasets on pressures retrieved/modelled?
	8. How are geospatial datasets on environmental components retrieved/modelled?
Data preparation/ transformation	*9. How is input data transformed?*
	10. Is resolution customizable?
Human activities	*11. How many human activity datasets are considered?*
Pressures	*12. What pressures are considered in the CEA?*
	13. How are land-based activities included into the pressure model?
	14. How are pressure distances defined?
	15. How is pressure propagation modelled in the CEA?
	16. Are multiple pressure effects taken into consideration?
Environmental Components	*17. How many environmental components datasets are considered?*
	18. Is the distribution of environmental component modelled?
	19. If, yes how is the distribution of environmental components modelled?
Pressure-environmental component interaction	*20. Does the model take into account non-linear response of environmental components to the pressure?*
	21. What pressure-effect interactions can the CEA take into consideration?
CEA Model Assumptions	*22. What are key assumptions in the CEA implemented in the different DST?*
Uncertainty	*23. Is/will uncertainty analysis included as operational instrument in the DST?*
	24. How is context uncertainty considered in the CEA?
	25. How is model uncertainty considered in the CEA?
	26. How is input uncertainty considered in the CEA?
	27. How is parameter (data) uncertainty considered in the CEA?
	28. How is model outcome uncertainty considered in the CEA?
Output	*29. What are the outputs of the CEA model application?*