Autonomous Job Analysis
A Method for Design of Autonomous Marine Operations

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Abstract— **Increased use of autonomy is considered crucial for continued growth in maritime industries like oil- and gas, waterborne transport, and fisheries- and aquaculture. This article presents a method called *Autonomous Job Analysis* (AJA), which purpose is to guide the design of autonomous marine operations. AJA breaks down the operation, and focuses on autonomy early in the design phase. The method uses elements from Hierarchical Task Analysis (HTA), and the execution of the analysis is influenced by HAZard and OPerability (HAZOP) studies. The proposed method is illustrated through application on two different case studies: Inspection of mooring lines in a sea-based fish-farm, and imaging of plume extension caused by discharge from a waste water plant.**

I. INTRODUCTION

The SINTEF group is the largest independent research organization in Scandinavia. As a response to the increased extent and complexity of autonomy introduced in operations at sea, SINTEF has established a corporate sponsored program called SEATONOMY. SEATONOMY is an effort to solidify and expand current practices within autonomy engineering, and to make the threshold for industrial adaptation of autonomy as low as possible.

SINTEF defines an industrial autonomous system as an autonomous unit that can operate safely and effectively in a real world environment while doing operations of direct commercial value and which can be manufactured, maintained, deployed, operated and retrieved at an acceptable cost relative to the value it provides, [1].

Autonomous Job Analysis (AJA) is a structured approach for design, development and validation of autonomous functionality, and one of the suggested tools in the SEATONOMY methodology, [1]. The purpose of the AJA method is to:

- Analyse and break down an existing operation, or an operation which is to be designed into manageable sub parts.
- Uncover overall operational modes, design challenges, needs and limitations regarding autonomous behaviour.
- Force the designer to consider autonomy critical aspects early on, e.g. communication, safe-states, human-machine interface, etc.

A. Motivation

Oil- and gas, waterborne transport, fisheries- and aquaculture, are maritime industries where autonomy and automation are considered key technologies for continued growth, see e.g. [2], [3] and [4]. In [5] it is pointed out that "on the Norwegian Continental Shelf, the 'easily' recoverable resources have already been exploited. The remaining resources are more challenging and require further emphasis on research and development". This motivates development and testing in order to establish more modern technologies.

The motivation for the SEATONOMY project has its roots in the SINTEF project MUNIN which designs an autonomous freight vessel system. In MUNIN cargo ships are considered, which will be able to traverse their route completely unmanned without human presence on board [6]. The dry bulk carrier has the greatest potential for becoming completely autonomous as it, according to [4], is "rather slow, operates on long distances with only one loading and one discharging port, and transports cargo that does not require much in terms of human supervision or intervention during the voyage". This application of autonomy improves the economic sustainability through reduced crew expenses. It also improves environmental sustainability through reduced fuel consumption and emissions by making "'slow steaming"' crossings a feasible option. An expected social impact is increased safety since human errors is one of the main causes of ship incidents worldwide [7]. An autonomous, unmanned vessel will also relieve officers from routine tasks and let them focus on more cognitively demanding and challenging tasks in a shore side operations centre [4].

B. Previous work

In the present paper, the authors present a new method called AJA. This method is based on principles used in Hierarchical Task Analysis (HTA), which is considered as the "best known task analysis technique" [8]. The original formulation of HTA was proposed in [9] according to [10]. It has its roots in the work of Taylor in the early 1900's, which was conducted in order to determine the best way to organize a generic manufacturing process.

The underlying principle is to break down a task into individual elements and study them. Among the different problems one has to face in task analysis procedures, is deciding what to describe and to what level of detail. This can be challenging, since it is not always obvious how to break down an operation in order to accomplish a representative analysis.

When using the task analysis technique as a method for breaking down an operation, "there is a tendency to fall into the trap of writing down the series of steps a human takes

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[...]", [10]. The correct way to analyse a task according to Sheridan [10] is to "specify the information required, the decisions to be made, the control actions to be taken". In [10] the HTA is defined by the following steps:

- Define the purpose of the analysis
- Define the boundaries of the system description
- Try to access a variety of sources of information about the system to be analysed
- Describe the operation by sub-operations, each defined by goals and sub-goals measurable in terms of performance standards and criteria.
- Keep the number of immediate sub-operations under any super-ordinate operation small
- Link goals to sub-goals
- Describe the conditions under which sub-operations and the are triggered
- Stop re-describing the sub-operations when you judge the analysis is fit-for purpose
- Verify the analysis with subject-matter experts
- Be prepared to revise the analysis

Although the method share some key properties with HTA, comprehensive reviews of HTA or other existing similar methods are not included in this paper. The interested reader is referred to [10] for a detailed description of HTA.

C. Scope

The purpose of this paper is to present a new method called Autonomous Job Analysis, intended to uncover overall operational modes, design challenges, needs and limitations regarding autonomous behaviour for marine operations.

The AJA method is one of the suggested methods in the SEATONOMY methodology, which provides a structured approach for design, development and validation of mobile autonomous maritime operations and systems. An overview of the SEATONOMY methodology can be found in [1]. SEATONOMY views the challenge of designing autonomous systems from three viewpoints, and the workflow is incremental and iterative, see Figure 1. AJA is a method to be used in the operational viewpoint, which concerns the overall design and specification of the operation.

The task analysis elements in [9] includes task description, behaviour modelling, risk assessment, hypothesis generation and cost-benefit analysis. We have chosen an iterative manner to keep the analysis to a manageable size, at the cost of perhaps having to perform the analysis over several iterations, including iterations where new information from other methods are taken into account. A diagram showing the different design phases in an engineering project is presented in Figure 2. It is indicated where AJA is most appropriate to be used.

D. Organization of document

The remainder of this paper is organized as follows: Section II contains an in-depth description of the AJA method. Section III and IV contains the main findings when the AJA method is applied to the two use-cases of mooring inspection and plume detection, respectively. Finally, a conclusion is

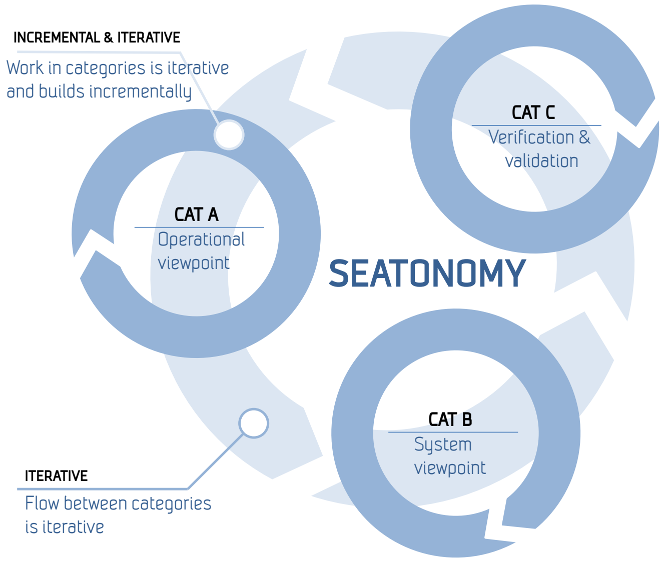

Fig. 1. SEATONOMY work flow

Fig. 2. AJA is performed early on in the design phase.

given in Section V, where as the Appendix I contains an overview of the nomenclature used and Appendix II an introduction to Levels of Autonomy (LoA).

II. Autonomous Job Analysis description

A. Requirements and advice to be followed a priori

The main purpose of the AJA method is to aid the design of autonomous marine operations by uncovering the overall operational modes and design challenges as well as needs and limitations related to autonomous behavior by breaking down operations into sub-operations and tasks and analyzing these individually. As a result, the method facilitates a common understanding between all stakeholders. For an autonomous operation related to oil- and gas the stakeholders could for instance be:

- An oil company that needs the operation to be executed.
- An oil service company carrying out the physical operation.
- A company designing the autonomous operation.
- One or more companies developing the system needed to execute the operation.

There is not always a distinction like this, and the stakeholders could for instance all be from the same company. AJA may not only be used when designing new autonomous marine operations, but also for analyzing existing marine operations. AJA can reveal possible design flaws or be used as a tool for design improvements. AJA is a team effort and requires close cooperation between people with different competence and backgrounds for best results. This will help designers in defining the correct goals and reach the desired result. Prior to AJA a unified understanding between all stakeholders of what the AJA is trying to achieve should be established. This could for instance be achieved by distributing a brief description of AJA, containing the main elements from this section.

B. Guidelines to be followed

When performing the analysis a meeting is required which is called the *AJA meeting*. The form of the meeting is motivated by the form of meetings used for HAZard and OPerability studies (HAZOP), which is "a structured and systematic examination of a planned or existing process or operation in order to identify and evaluate problems that may represent risks to personnel or equipment, or prevent efficient operation", [11]. The main goal of the AJA meeting is to gather and share all available information concerning the operation in question through cooperation between stakeholders. This information is then structured and gathered in a detailed list for sharing. The information can include, but is not limited to, constraints, limitations, restrictions regarding the software/hardware, money, human resources, and any kind of available information that can affect the design or the implementation of the operation.

A *proposed agenda* for the meeting can be as follows:

1) Introduction and presentation of participants.
2) Presentation of the main goal(s) of the operation.
3) Presentation of the AJA method.
4) Recapitulate the context definition and operation concepts.
5) Perform AJA (as far as possible).
6) Agree on further actions.

The meeting is driven by the *moderator* who is responsible for:

- Introducing the method to the client.
- Leading the discussion.
- Ensure completeness of the analysis.

The moderator could be from the team designing the operation, or hired from an external company specializing in leading these kinds of meetings. It can for instance be desirable to use a independent third party which does not favour either the stakeholders.

The *secretary* is responsible for:

- Preparation of the AJA table, see Table I and Figure 3.
- Recording the discussion.
- Version control of the AJA table/flow chart.

The AJA table consist of a series of questions to be answered, and is described in detail in Section II-C. The meeting participants should be experts within various aspects of the operation. Meetings including a large number of participants tend to become inefficient and hard to manage. If it is likely that the total number of participants needed exeeds 8-10, then dividing into smaller meetings should be considered. The responsibilities of the participants are the same as for participants as HAZOP meetings ([11]):

- Be active! Everybody's contribution is important.
- Be to the point. Avoid endless discussion of details.
- Be critical in a positive way not negative, but constructive.
- Be responsible. The person who knows should let others know.

It is unlikely that all questions can be answered during a single AJA meeting even if the total number of participants is kept low. 'Further actions' could therefore be to choose one or more responsible to actively seek out the relevant or missing information through experts or written material. The AJA table should be updated with this new information, or at least with reference to documentation available elsewhere, before it is distributed among the stakeholders. The person(s) responsible can be chosen from the operation design team, or from the client's team. The client may have relevant experts in his/her company, even if these experts did not attend the AJA meeting. If a large operation is to be analyzed, it may be necessary to perform AJA over several meetings. This gives the opportunity to include new or additional experts to add different perspectives of the operations.

It is important that new participants are brought up-to-date before the meeting in order not to waste time. In the beginning of the meeting the requirements/context specification should be agreed on.

The *Autonomous Job Analysis* consists of the following steps:

1) Describe the main goal of the operation
2) Divide into sub-goals, based on e.g. sequence, parallel behaviour or choices
3) Answer the list of AJA questions described in Table I
4) For each sub-goal, go to step 2 and repeat until goals become trivial tasks

The following steps are required during *post processing*:

1) The details from the AJA meeting should be processed and distributed among the stakeholders.
2) The stakeholders give feedback for possible subsequent iterations.

Another fact that needs to be considered is the presentation of the AJA method by the moderator. Describing an operation in a clear and informative way is challenging. Different authors prefer different template representations when describing operations. A variation between tables, lists, flowcharts have been proposed and the most common templates are presented in [10]. In the SEATONOMY methodology, the table representation has been proposed, followed by a flowchart to show the main progression of an operation. The table can, for instance, easily be implemented in Excel, as illustrated in Figure 3.

C. AJA table formulation

The AJA table consists of rows representing goals and sub-goals, as well as the questions to facilitate a detailed analysis of the operation under evaluation. The rows under

ID	Name	Description
1	Description of sub-goal	Give a short description of the sub-goal, focusing on the objective without too much technical detail. Achievement of the sub-goal should contribute to the achievement of a goal at a higher level, and eventually the main goal of the operation.
2	Communication	Communication flow: What key information needs to be communicated? Communication restrictions: What are the limitations?
3	Perception	Which information about the environment and the system itself must be available?
4	What are the criteria for success?	List design criteria which specify whether the sub-goal has been achieved. This can, for instance, be performance specifications related to accuracy or time.
5	What can go wrong?	Is there anything that can prevent the sub-goal from being successfully accomplished? Be specific about what characterizes abnormal behavior.
6	What is the operational safe state?	Define what state or mode should the system should go to, in order maintain the safety of the operation in the best possible way.
7	What is the human-machine interaction?	Describe the human-machine interaction. The interaction can be described in words, or with reference to some taxonomy for Levels of Autonomy, for instance as given in Table III in Appendix II .
8	Are there other premises or requirements for successful execution?	Describe other relevant premises for successful execution of the sub-goal.
9	Notes and comments	Add comments that are relevant for the sub-goal, but are not captured by the previous questions in the table.

TABLE I

AJA QUESTIONS

	Main goal of operation:	#Name of operation
ID	Question	Answer
1	Description of sub-goal	#TODO
	Communication	
	Perception	
	Success criteria	
	What can go wrong?	
	What is the oper. safe-state?	
	Level of autonomy	
	Other premises/requirements	
	Notes/comments	
1.1	Description of sub-goal	#TODO
	Communication	
	Perception	
	Success criteria	
	What can go wrong?	
	What is the oper. safe-state?	
	Level of autonomy	
	Other premises/requirements	
	Notes/comments	
2	Description of sub-goal	#TODO
3	Description of sub-goal	#TODO
4	Description of sub-goal	#TODO

Fig. 3. AJA template in Microsoft Excel

goals or subgoals are called "Communication", "Perception", "Success Criteria", "What can go wrong", "What is the operational safe state", "Levels of Autonomy", "Other premises/requirements" and "Notes". In addition, two rows that corresponds to the notes and the comments are appended. Depending on the operation and the available information, the table can be modified by adding or removing questions as necessary. Figure 3 exemplifies a possible generic representation of an AJA table.

D. *Output*

The output is a structured description and breakdown of the operation with each sub-operation is individually analyzed based on technological and operational constraints uncovered by the AJA meeting.

III. Case study: Mooring inspection

The purpose of the operation is to inspect mooring lines in a sea-based fish farm. The mooring system is critical for the integrity of the sea pens, and systematic inspection of ropes, wires and anchors may reveal damages on an early stage. This use-case also comprises highly relevant problems to be addressed within the offshore industry, for instance inspection of pipelines, risers and mooring lines. Varying sea current, risk of collision, and operation in partly unstructured environments, set high demands to safety. It is therefore important to develop a predictable autonomous system, with the correct degree of autonomy for all the working tasks.

A. *Requirements and context specification*

During concept exploration with SINTEF Fisheries and Aquaculture AS, different means for surveillance of mooring lines were considered. choosing an AUV instead of, for instance, a remotely operated vehicle (ROV), is due to the fact that a ROV requires support of a surface vessel. An AUV, on the other hand, can be launched and recovered manually from both boat and shore. Logistically, a boat to bring personnel and the AUV to the fish farm is still needed. To ensure safe operation, the inspection should only be performed for a given set of sea-states as exemplified in Table II. Wave height affects safe launch and recovery of the AUV. The operation must not under any circumstances allow fish to escape. Environmental impact, such as pollution, should be kept as low as possible. To reduce complexity, the operation is limited to inspection of one side of the frame mooring as illustrated in Figure 4.

B. *Main finding by AJA*

The main findings from the AJA are as follows:

- A total of seven sub-goals were found. First 'launch', 'find start point for inspection' are executed in sequence. Then 'follow line' and 'capture geo-tagged images/footage' are executed in parallel. The sub-goal 'analyse image/footage', is then performed. If the quality of the images/footage is acceptable, 'recovery' is executed. If this is not the case, the AUV will restart its mission from 'find starting point for inspection'. Finally,

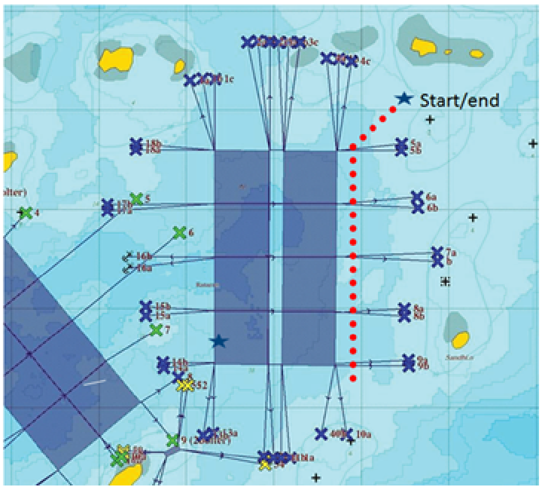

Fig. 4. Cages are given in dark blue. The proposed start and end points of the AUV mission are denoted by stars. The proposed AUV path is given in red dots.

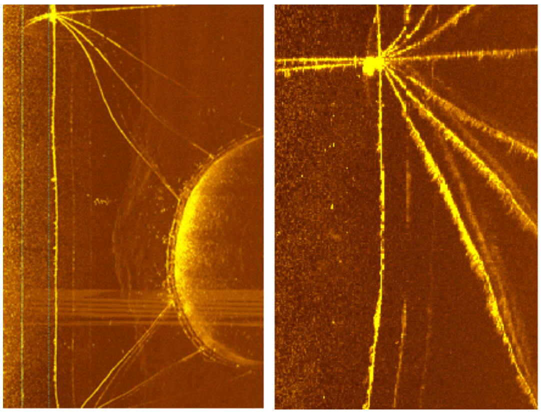

Fig. 5. Sample images of what mooring lines look like using a side-scan sonar.

the sub-goal 'go to safe state/be found' is triggered by failures in, for instance, the navigation system or the communication system.

- A side-scan sonar is considered the most useful sensor technology for this operation. A sample image of what mooring lines look like with a side-scan sonar is given in Figure 5.
- The question of whether the AUV should resurface or not in order to forward information to the operator is determined by the communication bandwidth, desired LOA and on-board intelligence. It could be possible to do on-board video processing, thereby realizing a more autonomous inspection, but the development of such intelligence is considered too costly and time consuming for this operation. Acoustic underwater communication bandwidth is limited when compared to i.e. radio communication in air. Real-time review of sensor data by a human operator is therefore considered unfeasible. For this case, the solution is to let the AUV to surface having reached the end of a mooring. At the surface, the AUV then transmits georeferenced footage to a human operator deciding whether or not the imagery is of high enough quality.
- The analysis also revealed that it would have been beneficial if mooring lines were equipped with active beacons or passive markers that can be easily identified by a side scan sonar. This can improve relative localization and navigation.

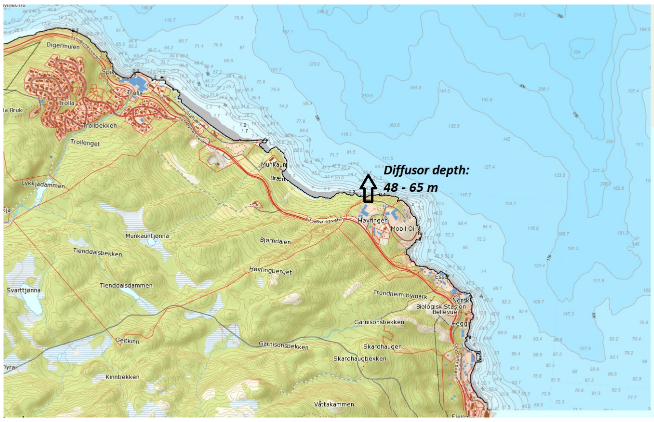

Fig. 6. Map of the Høvringen treatment plant

IV. Case study: Plume detection

The city of Trondheim has a treatment plant at Høvringen, approximately 3 km to the northwest of Trondheim harbour, which outlet is at 48-65 meters depth in the Trondheim fjord. There has been a major concern for waste resurfacing, and many models have been proposed in order to predict the outcome of a possible discharge.

The objective is to map the geographical distribution of the plume from discharge to intrusion using a conductivity sensor to record the interface between sewage and sea. The demonstrator will be a test of the possibility of utilizing autonomous vehicles for subsea mapping of regular and acute discharges of various origins. The use-case is suitable for evaluating the AJA since autonomy will be relevant for mission planning, navigation/motion control and for interpretation of sensor data. Sensor data from the plume will be merged into existing modeling tools at SINTEF (e.g. Dose-related Risk and Effects Assessment Model (DREAM)). In this respect, the use-case will also contribute to the validation of SINTEF's modeling tools and the complete measurement- and modeling toolbox that SINTEF can offer for discharge estimation.

A. Requirements and context specification

SINTEF Materials and Chemistry was the use-case owner, and could inform that a series of arrangements must be made in advance in order to ensure the success of such an operation. For instance, the person in charge at the treatment plant would have to be contacted in order to get approval for the experiments, information about the plume discharges, and possibly access to necessarily facilities. As in the previous use-case, operating conditions at which the experiments could be performed would have to be agreed upon, for instance based on the example in Table II. For safety reasons, it is important to inform traffic that passes close to the shore at Høvringen. An AUV was chosen to be used to detect the distribution and shape of the plume. Previous experiments have been based on fixed sensors, and have not given the desired spatial- and temporal resolution. An evaluation of available sensors and relevant parameters,concludes that a spatial mapping of the salt concentration is fit for this purpose. Based on existing models and previous experiments, some knowledge of the plume is known in advance. The equilibrium level of the plume is below the surface, and the equilibrium layer of the plume is about 4 meters high. The diameter of the plume is about 20 meters. The plume will move with the ocean current, and it is desirable that the AUV follows the plume for about 100-200 meters. Expected sea currents are 10-20 centimetres per second.

To acquire the necessary information about the direction of the plume, it was decided that either a recorded Doppler current profiler mounted on a surface vessel would be needed, or the AUV would have to be equipped with an acoustic Doppler current profiler. Failure to decide the direction of the plume, could possibly make the operation inefficient as the AUV would have to spend a considerable amount of time searching for the plume.

B. *Main finding by AJA*

The main findings by the AJA are summarized below:

- AUV motion planning consists of two concepts. The first concept is to utilize a priori knowledge (models and experiments) in combination with sea-current measurements at the start of the operation to generate a pre-planned AUV path. The preplanned AUV path would only be updated when the second concept, which is real-time sensor-based mission/path-planning, can be applied.

  Mapping of the plume should be performed by first planning horizontal lawn-mower patterns at fixed depth, speed and grid-size oriented perpendicularly to the sea current. Then make a similar plan for AUV motion parallel to the sea current, before gradually introducing autonomy in the path-planning algorithms by allowing the AUV to change speed, depth, grid-size and general direction based on salinity and sea current measurements.
- A total of seven main sub-goals were identified:‘detect direction and speed of sea current in real-time’, ‘plan path and transfer to AUV’, ’reach starting point with AUV’, ’follow (and update) preplanned AUV path’, ’surface and transmit measurements’ and ’recover AUV’.
- The execution of a sub-goal is initiated if the previous sub-goal is successfully accomplished. For instance, the sub-goal ’recover AUV’ depends on whether all the experiments have been executed.
- Possible causes for mission failure were uncovered during the AJA. Examples are too strong sea current for the AUV to follow its desired trajectory or, in the case of model based planning, that the plume is heading in a different direction compared to initial expectations. Less mission specific failures could be due to hardware and software failures and and inability to receive fix from global navigation satellite system when surfacing.

V. Conclusion

In this paper we have presented AJA, a method tailored for the design of autonomous marine operations. By analyzing and breaking down an operation, design challenges, needs and limitations regarding autonomous behavior are revealed. Furthermore, AJA facilitates communication, and enhances the understanding between stakeholders. Better communication and information flow between stakeholders, increases the likelihood of designing a successful autonomous system.

Two use-cases have been analyzed using the proposed method. It became apparent that increased autonomy would come at the cost of increased complexity and cost. The additional development cost associated with increased autonomy, can sometimes be circumvented by keeping the human operator in the loop. For example, humans have a tremendous capability when it comes to analyzing and understanding imaging data. The proposed method, together with other methods in the SEATONOMY methodology are fundamental to designing operations and systems with the *right* degree of autonomy.

Appendix I
Nomenclature

Agent The word agent denotes a physical entity performing the whole or some part of the operation.

Autonomy The ability of an engineering system to make decisions about its own actions while performing a task, without the direct involvement of an exogenous system or operator.

Method The word method is used as a structured way (e.g. sequence of steps, collection of questions) of acquiring certain knowledge. In SEATONOMY, this knowledge should help in designing the autonomous operation or system in a better way.

Methodology In SEATONOMY the word methodology is used as the analysis of the methods applied to designing autonomy for marine systems. The methodology offers a way to understand which methods, techniques or best practices can be applied to specific cases in order to achieve the best results.

Operation The operation is the mission, job, task or procedure intended to be performed by the system, and has a main goal associated with it.

Operational safe state A state or mode of operation an agent or system can enter in the case of an unwanted/unexpected event that cannot be handled in a determined way. This state or mode is one where the chance of harming itself or its environment is as small as reasonably possible.

Sub-operation An operation can be subdivided into smaller parts, e.g. procedurally, in parallel, or conditionally.

Beaufort number	Description	Wind speed	Wave height	Decision
1-4	Calm to moderate breeze	$\leq 7.9\,\mathrm{m\,s^{-1}}$	$\leq 2\,\mathrm{m}$	Proceed
5	Fresh breeze	$8\,\mathrm{m\,s^{-1}}$–$10\,\mathrm{m\,s^{-1}}$	$2\,\mathrm{m}$ to $3\,\mathrm{m}$	Decide on site
6-12	Strong breeze to hurricane	$\geq 10.8\,\mathrm{m\,s^{-1}}$	$\geq 3\,\mathrm{m}$	Suspend operation

TABLE II

SUITABLE ENVIRONMENTAL CONDITIONS FOR PERFORMING THE OPERATIONS.

These smaller parts are named sub-operations in SEATONOMY.

System The system is the human-machine solution proposed to solve the operation.

Task A definite piece of work that has been assigned, or expected to be completed.

APPENDIX II
LEVELS OF AUTONOMY

The human-machine interaction and cooperation can be expressed by various levels of autonomy (LOA). Each of these levels specify a different degree to which a task is automated. This implies that automation is not all or none, but can vary across a continuum of intermediate levels, between fully manual performance and full automation at the two extremes. Several different LOA between the two extremes have been proposed by different researchers, resulting in numerous different taxonomies regarding the interaction between human and machine. A good starting point is [12], which summarizes the development of the LOA Assessment Tool, a method for determining the appropriate level of autonomy to be designed into each function within a system. A survey of the taxonomies of LOA as well as different approaches available to the readers can be found in [13]. A simple example of a taxonomy of LOA is presented in Table III, and consists of 6 different levels varying from fully manual to autonomous control as presented in [14].

LOA	Name	Description
1	Human operated	*All activity within the system is the direct result of human-initiated control inputs.* The system has no autonomous control of its environment, although it may have information-only responses to sensed data.
2	Human assisted	*The system can perform activity in parallel with human input, acting to augment the ability of the human* to perform the desired activity, but has *no ability to act without accompanying human input.* An example is automobile automatic transmission and anti-skid brakes
3	Human delegated	*The system can perform limited control activity on a delegated basis.* This level encompasses automatic flight controls, engine controls, and other low-level automation that must be activated or deactivated by a human input and act in mutual exclusion with human operation.
4	Human supervised	*The system can perform a wide variety of activities given top-level permissions or direction by a human.* The system provides sufficient insight into its internal operations and behaviors that it can be understood by its human supervisor and appropriately redirected. The system does not have the capability to self-initiate behaviours that are not within the scope of its current directed tasks.
5	Mixed initiative	*Both the human and the system can initiate behaviours based on sensed data.* The system can coordinate its behaviour with the human's behaviours both explicitly and implicitly. The human can understand the behaviours of the system in the same way that he understands his own behaviours. A variety of means are provided to regulate the authority of the system with respect to human operators.
6	Fully autonomous	*The system requires no human intervention to perform any of its designed activities* across all planned ranges of environmental conditions.

TABLE III

LEVELS OF AUTONOMY [14]

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