North Sea Energy offshore system integration

1.2

North Sea Energy 2020-2022

Activity interdependency exploration

North Sea Energy 2020-2022

Unlock the low-carbon energy potential North Sea with optimal value for society and nature

The North Sea Energy program and its consortium partners aim to identify and assess opportunities for synergies between energy sectors offshore. The program aims to integrate all dominant low-carbon energy developments at the North Sea, including: offshore wind deployment, offshore hydrogen infrastructure, carbon capture, transport and storage, energy hubs, energy interconnections, energy storage and more.

Strategic sector coupling and integration of these low-carbon energy developments provides options to reduce CO2 emissions, enable & accelerate the energy transition and reduce costs. The consortium is a public private partnership consisting of a large number of (international) partners and offers new perspectives regarding the technical, environmental, ecological, safety, societal, legal, regulatory and economic feasibility for these options.

In this fourth phase of the program a particular focus has been placed on the identification of North Sea Energy Hubs where system integration projects could be materialized and advanced. This includes system integration technologies strategically connecting infrastructures and services of electricity, hydrogen, natural gas and CO2. A fit-for-purpose strategy plan per hub and short-term development plan has been developed to fast-track system integration projects, such as: offshore hydrogen production, platform electrification, CO2 transport and storage and energy storage.

The multi-disciplinary work lines and themes are further geared towards analyses on the barriers and drivers from the perspective of society, regulatory framework, standards, safety, integrity and reliability and ecology & environment. Synergies for the operation and maintenance for offshore assets in wind and oil and gas sector are identified. And a new online Atlas has been released to showcase the spatial challenges and opportunities on the North Sea. Finally, a system perspective is presented with an assessment of energy system and market dynamics of introducing offshore system integration and offshore hubs in the North Sea region. Insights from all work lines have been integrated in a Roadmap and Action Agenda for offshore system integration at the North Sea.

The last two years of research has yielded a series of 12 reports on system integration on the North Sea. These reports give new insights and perspectives from different knowledge disciplines. It highlights the dynamics, opportunities and barriers we are going to face in the future. We aim that these perspectives and insights help the offshore sectors and governments in speeding-up the transition.

We wish to thank the consortium partners, executive partners and the sounding board. Without the active involvement from all partners that provided technical or financial support, knowledge, critical feedback and positive energy this result would not have been possible.

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Activity interdependency exploration

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1 Introduction

Situation sketch of energy system development for the North Sea Area

Unlocking the potential of the North Sea for the European energy transition is considered as one of the key activities towards achieving a climate neutral economy by 2050. The North Sea area provides the opportunity of deploying low-carbon energy solutions such as offshore wind, carbon capture and storage (CCS), offshore hydrogen production transport and storage, and energy islands and storage. To this end, existing end-of-life gas infrastructure can even strategically be used or repurposed to support these low-carbon energy solutions.

The North Sea Energy program is directed at exploring the value of these offshore solutions and assessing how such solutions should jointly be developed. Additionally, the North Sea Energy program aims to identify opportunities for establishing synergies between energy sectors and related partners to support decision making and development. Orchestrated as a public-private partnership, the North Sea Energy program includes a large number of international partners, each with different perspectives, motivations and challenges faced. They jointly work on developing, installing and operating offshore energy systems the North Sea area. Such offshore energy systems may comprise subsystems such as natural gas systems, offshore wind farms, hydrogen production systems and carbon capture and storage systems which offer great potential for synergies and joint energy solutions, but are also highly interdependent.

Complex decision making as a result of interdependent system development

Given the significant interdependencies between systems to be developed on the North Sea, the (long-term) activities to be conducted to support the roll-out of offshore energy systems become intertwined and tangled up, creating a highly complex project structure to navigate, both from a systems perspective as well as a development and execution perspective. In working towards the implementation of low carbon solutions, many decisions have to be made that are highly dependent on decisions made elsewhere for the project, but also affect decisions in the future. More so, these interdependencies are not always clear nor does their impact become apparent. As a consequence, acting as a 'first mover' is considered risky: investments made for new low-carbon solutions may not generate return on investment if other stakeholders do not make decisions supporting these investments or unnecessarily prolong decision making. This in turn results in a stalemate in which North Sea Energy stakeholders are seemingly waiting on each other without any progress towards system development and implementation.

Research objective and research questions

To break such a stalemate and to foster collective decision making, holistic insights on the interdependencies between activities for the North Sea Program are needed. To do so, in this report, we conduct a first exploration and analysis of the interdependencies that exist for activities to be conducted for the North Sea Energy project. Such an *activity interdependency analysis* can help in identifying what activities should be conducted early on for the project as other activities for the project significantly depend on its outcomes. In doing so, this can contribute to understanding what actions or decisions should be taken *as soon as possible* and what stakeholders should be involved. Additionally, it can make explicit how (sub)systems are interrelated and what opportunities for synergies between systems can be identified. In doing so, we aim to provide input towards decision making on how energy systems should be integrated (considered as part of WP1 for the NSE project), as well as provide input towards decision making on what actions and decisions should be made first to support and potentially accelerate the developments within the project (considered as part of WP7). Accordingly, we aim to address the following research questions:

- What interdependencies exist between activities to support the development of offshore energy systems in the North Sea Area?
- Based on the interdependencies mapped, what lessons can be learned in terms of system integration for offshore energy systems in the North Sea Area (WP1)
- Based on the interdependencies mapped, what key recommendations can be presented in terms of actions and decisions to be taken to accelerate the development of offshore energy systems in the North Sea Area (WP7).

Research approach

To support the mapping and subsequent analysis of interdependencies within the North Sea Energy project, we use a methodology based on design structure matrices (DSM) (Browning 2001). Such design structure matrices are generally used to clarify interdependencies for large complex systems or projects. Additionally, DSMs support the application of algorithms towards clustering and sequencing of such systems to provide insights on the timing of their execution or development. In this report, we focus on activity-based DSMs, analysing the sequence of activities to be conducted for the North Sea Energy project per (sub)system as well as their interrelationships.

Structure of report

The remainder of this report is structured as follows. In Section 2, we elaborate on the background with respect to design structure matrices, and detail algorithms that can be used to support the analysis of such matrices. In Section 3, we delineate the research design we have followed for our research to provide answers to our research questions. In Section 4, we describe how the DSM was constructed for North Sea Energy, as well as indicate the longlist of interdependencies generated through our search. In Section 5,, based on the longlist of interdependencies and the resulting DSM, we synthesize and describe the lessons learned regarding systems integration (WP1) and road mapping (WP7). In Section 6, we conclude this work and provide pointers for future research efforts.

2 Background literature: Interface management

In this section, we detail the background literature to our work. Specifically, we elaborate on the use and application of Design Structure Matrices (DSMs), and highlight how DSMs can aid decision makers in engineering or project management related settings or domains. Next, we discuss relevant algorithms that serve as the basis for the application of DSM, and motivate our selection of the algorithms that we will use for the remainder of this work.

2.1 The basics: an N^2-matrix

For analyzing and monitoring the interfaces between objects (e.g. systems, activities, organizations), the so-called N2-chart can be used (also known as an N-squared chart). In this matrix all interfaces between the system components can be mapped. The N2-chart is a simple technique to map relationships between system components. Horizontally, the inputs of the system components are given. Vertically, the outputs of the system components are given.

	Subsystem 1	Subsystem 2	Subsystem 3	Subsystem 4
Subsystem 1	No Entry	Interface S/S 1 – 2	Interface S/S 1– 3	Interface S/S 1 – 4
Subsystem 2		No Entry	Interface S/S 2-3	Interface S/S 2-4
Subsystem 3			No Entry	Int[illegible] S/S 3-4
Subsystem 4				No Entry

In principle, each cell in the table is a potential interface that needs to be controlled. In matrix form, this means that each interface between two systems occurs twice: once with system A as the leading system and system B as the following system, and once with system A as the following system and system B as the leading system.

The objects should be detailed such that each subsystem or activity as a whole is the responsibility of one stakeholder. This is necessary to allow for clear communication. Each identification of an interface immediately identifies an issue that will be discussed and monitored with the appropriate owners of the object.

2.2 Design Structure Matrix

A Design Structure Matrix (also referred to as Decision Structure Matrix, Dependency Structure Matrix or DSM) is a highly flexible, network modelling method generally used for systems modelling to analyse (often complex) systems in terms of their subsystems and the composition and integration of these sub systems (Browning 2001). A DSM (as also illustrated in Figure 1 represents a square matrix containing identical rows and columns that describe the elements such as objects, systems or activities that pertain to a system or project. Each cell on the diagonal consequently corresponds to the objects or activities listed for the rows and columns, whereas the off-diagonal cells describe *dependencies or relationships* that exist between different objects and activities. This dependency or relationship can be interpreted as *row-column* (e.g., element B provides input or influences element A) or as *column-row* (element A provides input to element B).

Using the DSM, one can capture and make explicit what (inter) dependencies or relationships exist for a complex system or project, which in turn can help in identifying key operational or executional requirements regarding the system and contribute towards decision making on how a project should be executed or how a system should be configured.

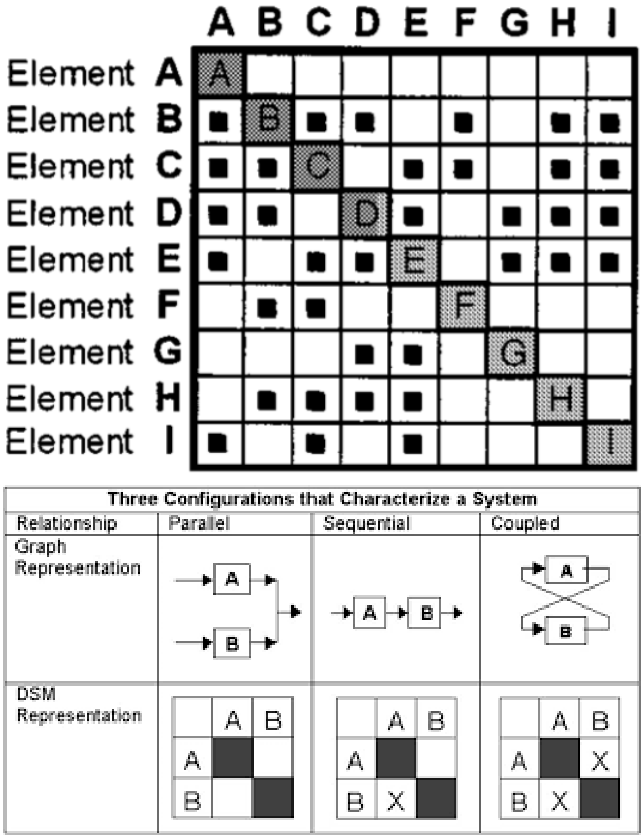

Figure 1: Example Design Structure Matrix (from Browning, 2001)

Generally speaking, two (non-exclusive) categories of DSMs can be distinguished: static DSMs and time-based DSMs (Browning 2001). Static DSMs describe the elements that exist concurrently for a system or project. For example, large machines generally consist of multiple components and subcomponents that interact with each other as part of its operations. Each individual component contributes to the functioning of the machine, but is also dependent on the input or actions of other (sub)components. Logically, it is valuable here to understand what *cluster* of components is valuable to consider (e.g. those components that heavily influence each other). Such clusters can help in understanding how the machine can be built incrementally or how maintenance can be conducted without affecting many other parts of the machine. As a result, *clustering algorithms* are frequently used to analyse static DSMs. On the other hand, time-based DSMs describe a flow of time: the order of the elements in either the row or column determines the sequence in which these elements are executed. Dependencies between elements consequently refer to ‘feedforward’ or ‘feedback’ relationships (Browning 2001). Figure 2 illustrates the difference by highlighting one feedback relationship in red.

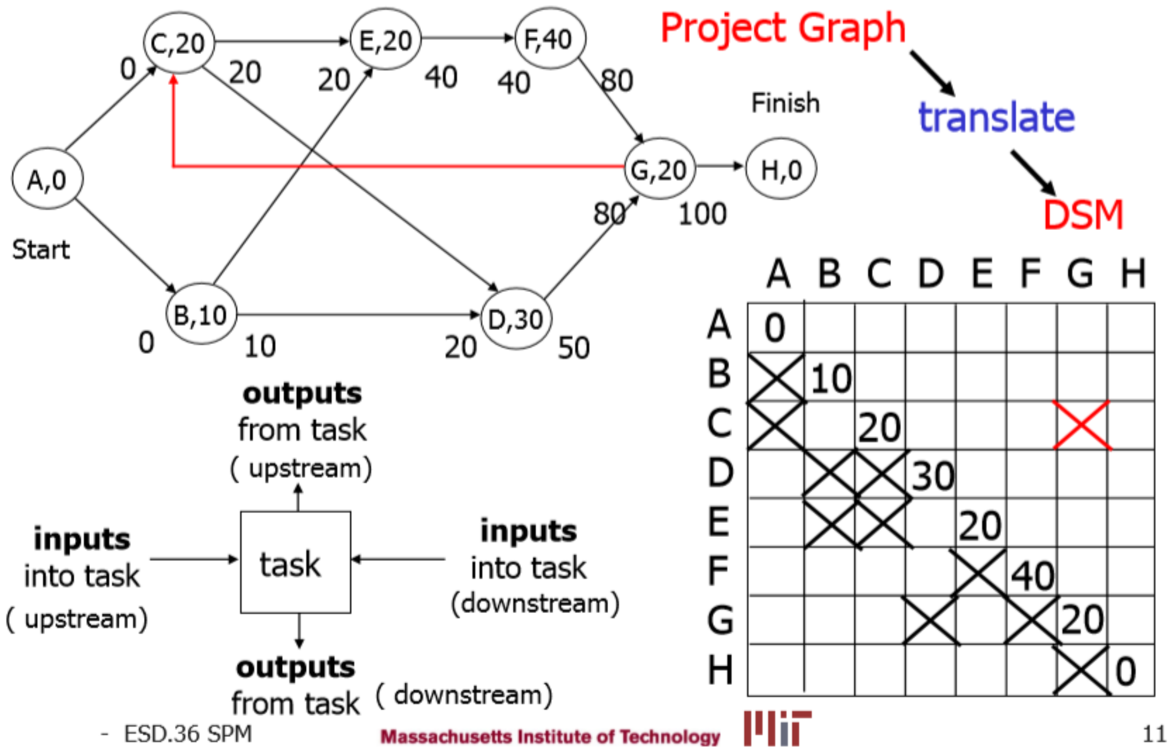

Figure 2: Feedback and feedforward relationships between activities

To analyse and improve on the ‘optimal’ sequence in time-based DSMs, *sequencing algorithms* are generally used. In the following section, we will detail several clustering and sequencing algorithms, and motivate our selection of algorithms to be used for our analysis of the North Sea Energy project.

2.3 Clustering and Sequencing Algorithms used to analyse DSMs

Several clustering algorithms exist to support the analysis of (static) DSMs (Browning 2016). The most basic clustering algorithm is the Markov clustering algorithm, which enables single level clustering: it divides the matrix into groups that based on their (inter)dependencies should be grouped together, such that when considering the entire matrix feedback loops are reduced as much as possible. The algorithm contains three tuning parameters *alpha*, *beta* and *mu* which are used to tune the size and number of clusters to be formed. Specialized forms of the generic Markov clustering algorithm exist, such as the multi-level clustering, local re-clustering and multi-level clustering with bus detection (Wilschut 2018). The former enables clusters *within* clusters to be created, allowing a hierarchical structure in terms of clusters to be produced, useful to understand what subclusters within a larger clusters can be identified – for example, large machines consist of an integrated set of components which in turn consist of integrated parts and elements which in general should be considered jointly. In Figure 3, an example of a DSM and identified clusters is provided. Local re-clustering enables the user to cluster within a cluster, *without* the need to consider other clusters. Lastly, multi-level clustering with bus detection targets the identification of bus components, e.g., sets of elements that relate to many other components or elements throughout the system, and thus make sense to consider separately (for example, a power supply unit influences all other components for a large machine) (Wilschut 2018).

For our work, we experiment with two different clustering strategies: 1) we build upon the clustering algorithms mentioned above to identify which activities should be jointly considered to support the system integration and 2) we declare initial clusters manually, based on expert judgement on which activities should be grouped together (e.g., activities that occur in the same subsystem or in the same life cycle phase).

Sequencing algorithms generally focus on reducing the amount of feedback loops that exist for a DSM (see Figure 4). Logically, this is connected to how the DSM initially is clustered (using clustering algorithms or a manual clustering strategy). To optimize the sequencing of a DSM, a combination of clustering and *branch sorting* or *branch-and bound* heuristics is often applied. Following a decision tree type of structure, branch sorting aims to determine which cluster or set of clusters should occur first given a pre-defined search or state space of branches (i.e. order of clusters) to consider in light of their relative performance. Logically, boundaries for the state space and the criteria used to determine performance can be altered based on the preferences of the user (for example, large cluster first or a given cluster should occur first).

For our work, we use sequencing algorithms and heuristics to understand which activities or set of activities should be considered *first* to ensure that feedback loops are reduced *as much as possible*, and to understand the implications of the sequencing of the clusters on the expected project execution.

Figure 3: a) Unclustered example of a DSM and b) clustered DSM (from (Wilschut 2018)).

Figure 4: Illustration of a sequenced process DSM (from (Wilschut 2018)).

3 Research design

In this section, we describe the research design we have followed to analyse the interdependencies that exist for activities to be conducted in the North Sea Energy project, and to investigate what can be learned from this analysis in terms of system integration (WP1) and road mapping (WP7). Our research design consists of 5 steps, namely (see Figure 5):

1. Identify systems and activities for the North Sea Energy project
2. Collect and map dependencies between activities identified
3. Construct DSM matrix
4. Apply sequencing and clustering algorithms and mechanisms
5. Analyze results of activity interdependency analysis

Figure 5: Methodology followed for activity interdependency analysis

In the next subsections, we detail each of these steps and explain what inputs and outputs are generated as part of each step.

3.1 Identify systems and long-list of activities

Input: **Documentation on NSE 1-4**
Output: **Longlist of activities to be conducted for the North Sea Energy project**

The first step of our research design concerned the identification of activities for systems and subsystems to be executed for the North Sea Energy project. As indicated, offshore energy systems (OES) may include several interrelated (sub)systems:

1. Natural gas systems (NG)
2. Offshore wind farms (OWF)
3. Carbon capture storage systems (CSS)
4. Hydrogen systems (H2)

Logically, each of these systems has its own lifecycle, as well as consists of subsystems and components that should be constructed. To express the lifecycle, general activities can be identified such as *orientation*, *design*, *construction*, *operation & maintenance* and *abatement* (Schuman and Brent 2005), which can be related to each of the high level systems in NSE and subsequently cascaded to the lower level systems / subsystems that exist. In this step, the goal was to understand the level of detail needed in terms of (sub)systems to consider to provide on the one hand enough structure and depth to conduct activity interdependency analysis but on the other hand to avoid redundancy of activities to be included (i.e., including activities that do not or only have very few relationships to others). The latter also aims to ensure that the analysis of the DSM matrix remains manageable and interpretable: a large longlist of activities can increase the complexity of analysing the DSM matrix or obscure its interpretation. This step was iterative in nature in conjunction with step 2.

A more detailed elaboration of this activity can be found in Section 4.

3.2 Collect information on and map dependencies between activities

As a next step, we focused on collecting information on the dependencies that exist between activities identified for the longlist. To collect this information, we built upon current documentation related to North Sea Energy (specifically, the final synthesis report for NSE3[1] and the preliminary draft report for NSE4. In addition to this, we conducted semi-structured interviews with work package leaders and relevant stakeholders in the North Sea Energy project to further complement the data collection process (including different perspectives on the project) as well as to access tacit knowledge that may exist regarding systems, activities or interdependencies. General information regarding this set of interviews is presented in Table 1. Through both information sources, a comprehensive understanding of the systems, activities and interdependencies to be included for the DSM matrix is obtained. Per interdependency, we also indicated whether this dependency was related to *policy and regulatory* (PRS), *techno-economics* (TE), or related to *spatial and environmental planning* (SE) and labelled the dependencies accordingly. In addition, any adaptations needed to longlist of activities needed (Step 1) as a result of this collection process (i.e. a need for more specificity on the longlist of activities) was iteratively resolved.

Table 1: Set of interviews conducted to support the elicitation of dependencies between activities

Interview	Domain / Perspective	Interviewer(s)	Date
1	RAMS	TH, AP, RG	3-12-2021
2	Logistics	TH, AP	6-12-2021
3	Regulation and policy	TH, RG	2-12-2021
4	Environment	TH, AP	26-11-2021
5	Societal Embeddedness	TH, RG	14-12-2021
6	System modelling	TH, RG	26-11-2021
7	Stakeholder perspectives	TH, RG	14-01-2022
8	GIS NSE atlas	TH, RG	14-01-2022
9	Ecology	TH, AP	26-11-2021
10	Techno-economic hubs	TH, RG, NB	17-12-2021
11	Long-term roadmap	TH, RG, NB	22-12-2021

A more detailed elaboration of this activity can be found in Section 4.

[1] https://north-sea-energy.eu/static/3e19bcb9aa57735fe1bbc423ca22d5e7/FINAL-North-Sea-Energy-Unlocking-potential-of-the-North-Sea-program-findings-2020.pdf

3.3 Construct the DSM matrix

Input: Understanding of systems, activities and interdependencies in NSE
Output: DSM matrix for NSE

The activity longlist generated as well as the interdependencies elicited served as the basis for the construction of the DSM matrix (see Figure 6). As a illustrated, the X- and Y-axis of the matrix comprise of the longlist of activities. This results in a matrix-like structure for which the diagonal represents the same activity for both the X- and Y-axis (which should remain blank as we assume that activities are not self-dependent). Using this structure, the dependencies *between* activities can be mapped. In terms of mapping the dependencies and interpreting the DSM matrix, we adopt the logic that on the *left side* of the diagonal, activities on the X-axis *provide input to / create a dependency for* activities on the Y-axis, whereas for the *right side* of the diagonal, this is vice-versa (i.e. activities on the Y-axis influence activities on the X-axis).

To support the construction of the DSM matrix, we modelled the preliminary matrix in Microsoft Excel. Here, we mapped the identified interdependencies to the DSM matrix to arrive at a first version of the DSM matrix for the North Sea Energy project. This matrix was internally validated with work package leaders. To ease the analysis of the DSM matrix, to categorize interdependencies and to enable the (automated) application of algorithms, we then imported to the DSM matrix to the online tool RATIO[2]. RATIO is a Python-based tool that enables users through DSM-based support to analyse and support decision making on complex systems or projects. It offers 'pre-coded building blocks' that can be integrated and combined to further detail the DSM matrix and to enable the application of algorithms towards the analysis of DSMs, serving as a robust structure towards achieving our objectives. A detailed description of how the matrix was constructed as well as the final version of the matrix is presented in Section 4.

[2] https://ratio-case.nl/

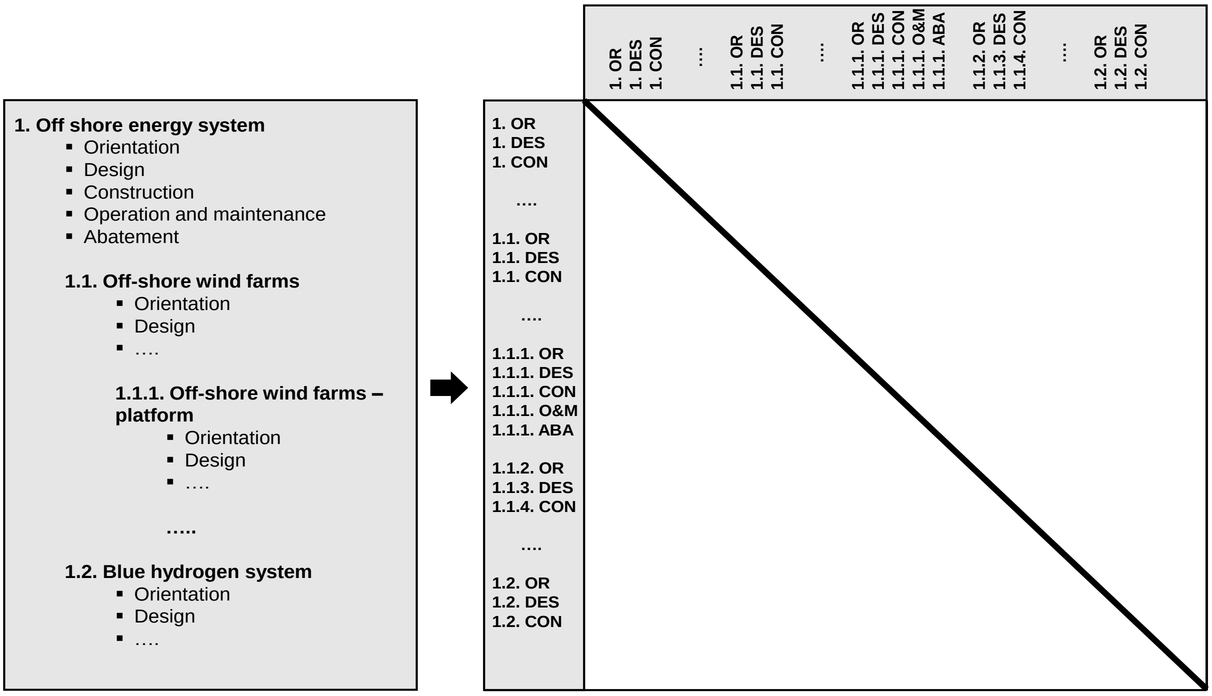

Figure 6: Construction of the DSM matrix

3.4 Apply sequencing / clustering algorithms and mechanisms

Input: **DSM matrix for NSE**
Output: **Modified representations of matrix to support the analysis of results**

For the fourth step of the research design, we applied sequencing and clustering algorithms and mechanisms in RATIO to analyse the derived DSM matrix and to identify configurations of the matrix that help in interpreting and explaining the results. Additionally, based on interpretation of the results received, this step also highlighted some of the interdependencies that were missing.

As highlighted in Section 2, a number of sequencing and clustering algorithms exist to support our analysis. To understand what sequencing and clustering algorithms and mechanisms worked best, we adopted a trial-and-error approach, interpreting the results generated after application of certain algorithms. First, we used *clustering algorithms* to understand what hierarchical structure of clusters can be identified for the project. Next, we applied *Tarjan's strongly connected components algorithm* (Tarjan 1972) and *branch sorting* to determine the most 'optimal' sequence to be followed based on our first version of the matrix. On the basis of the results obtained, we further improved the matrix and selection of mechanisms to support its analysis.

Through our analysis, several observation for improving the (use of the) DSM matrix were made. For example, application of sequencing algorithms led to logically incorrect sequences or clusters as the outcomes for the analysis (for example, *the abatement of a system* preceding *its orientation*). Here, we concluded that some dependencies should have more weight than others to reflect this behaviour. To enable this, we distinguished for our matrix that dependencies can be *preceding* (i.e. a dependent activity should not happen before the depending activity is completed) or *information* (e.g. PRS, SE, TE) of nature. *Precedence* dependencies consequently received a higher weighting to ensure that these dependencies follow a logical flow when clustered or sequenced. With did not add any weights to the information-based dependencies as this would have called for a comparison between the importance of information concerns (which is out of the time and scope of this research).

We also concluded that given the vast amount of interdependencies included (and the lack of explicit weighting for information dependencies), sequencing algorithms did not prove to be effective for generating interpretable results. As a result, we omitted the use of sequencing algorithms from our analysis and solely applied clustering algorithms and mechanisms to generate DSM-based results. Here, we also focused on clustering mechanisms that made sense from a logical point of view: for example, we applied clustering algorithms that group all activities related to the *orientation phase* of a certain system. Trial-and-error learning was used here to find representations of the DSM matrix that helped us in uncovering challenges and lessons learned for WP1 and WP7.

As a result of this process iteration, several interdependencies were also added to the matrix, particularly those to support the correct precedence / sequence of activities. Once no errors for the results were identified after application of the algorithms, we concluded our iterative process. The final results received consequently served as the basis for deriving the lessons learned for systems integration (WP1) and road mapping (WP7).

Working flow to support RATIO tooling

The workflow with the RATIO tooling presented in the aforementioned sections is illustrated in the following scheme. During this analysis, there have been several iterations. The input files have been adapted and upgraded. The environment preparation consists in the import of the needed packages, parts of the *ragraph* environment, necessary to create the matrix, run the analysis and illustrate the results. For each iteration, the selected input file were used, and the output are first qualitatively checked by a simplified visualization. The input files can be modified in the script, and can be later saved as new csv file. Finally the specific analysis that can be run and presented in Figure 7 is summarized by the green blocks.

The RATIO tooling works with two input files presented in a csv format, these two files contains the information regarding how the matrix is structured: the nodes file represents the list of activities, and what dependency and interdependency are determined between these activities is described in the edge file. The (inter)dependencies between the activity are defined in an iterative process. Therefore, once a new dependency is established, this can be added into the DMS matrix by following two processes: directly in the analysis phase, throughout the script, or adding the information in the edge file. The latter resulted in a more manageable and efficient way. Nevertheless, it is highly recommended to keep track of the changes in the edge files by implementing a version control history.

Each (inter)dependency can contain more information, among these, it can be provided a kind type. Initially there were differentiated two kinds: information and precedency. The precedency dependency were the ones necessary in the development phases, for example, the construction of the OWF can only start once the design of the OWFs has been completed. Later on, it has been decided to unify all the dependency with the kind information as in the analysis the differentiation was not providing further information.

The tool offers also the possibility to analyse the dependency based on “forced” orders/clusters of ‘nodes list’ . This means that the list of all the assets and their phases could be clustered on the needs. The root node specification allow to provide the intended order of the assets or of the lifecycles in the matrix. This allows to illustrate the analysis of the several dependency in a specific order.

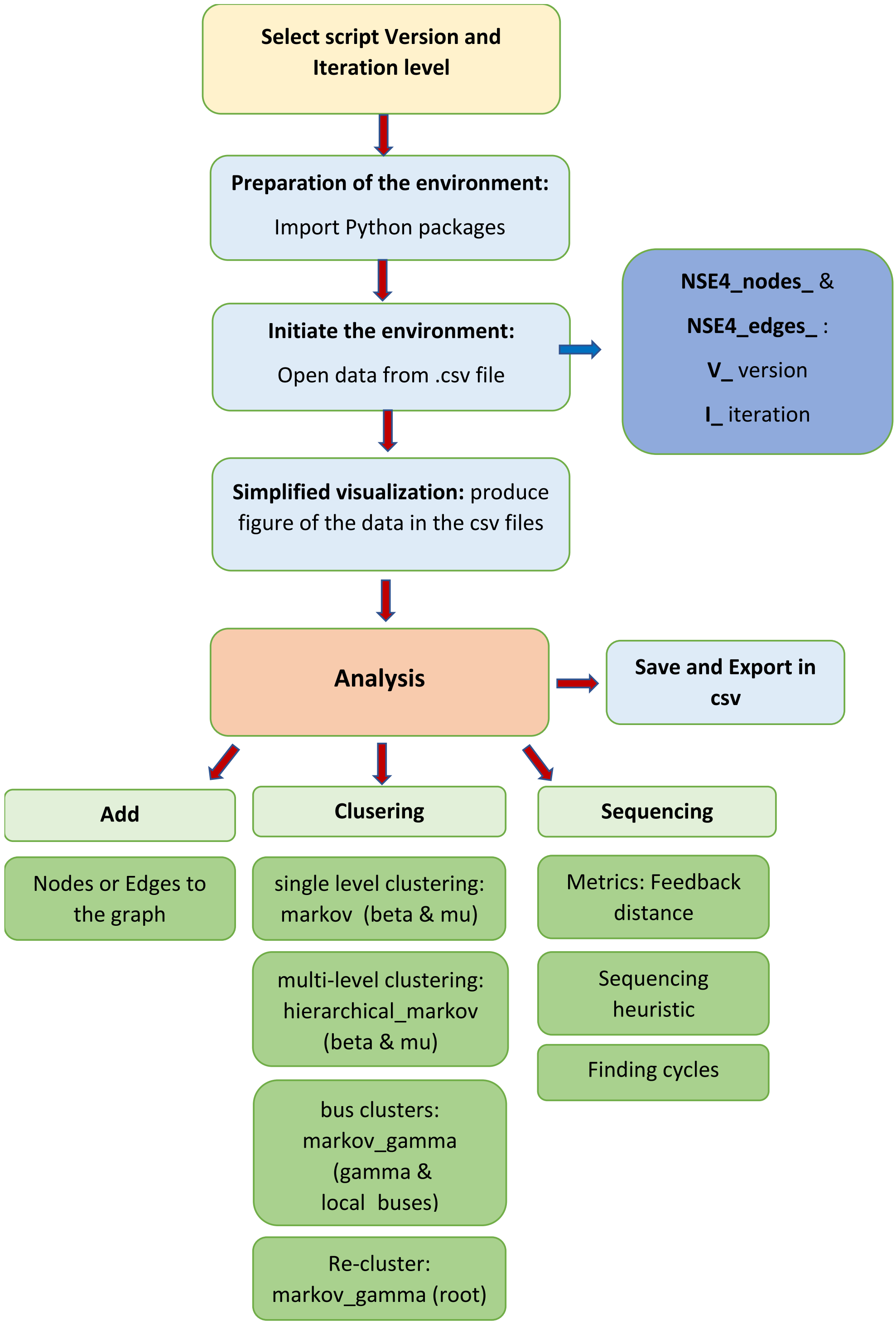

Figure 7: Python workflow to support DSM analysis in RATIO tooling

3.5 Analyze the results and provide insights for WP1 and WP7

The interpretation of the results generated by the RATIO tooling can either be algorithm-based or based on manual operations of the DSM in RATIO:

1) **Algorithm-based interpretations**: The DSM is clustered and/or sequenced by means of executing commands for clustering and sequencing in the RATIO software using the edge input file and thereby

changing the matrix rows and columns of the input node file. The results are then interpreted, documented and communicated as presented by RATIO.

2) **Manual interpretations:** Through trial and error and expert judgement, the nodes file is clustered and/or sequenced manually to develop a matrix that allows its user to identify, document and communicate information (inter)dependencies between activities based on the edge input file information visually available via the RATIO tool.

Depending on what type of results are expected, both (a combination of both) analysis methods can be used. For example, if an optimal sequence is to be determined, this can be supported by means of algorithm-based interpretation, providing ‘hard’ constraints on what this sequence should be (depending on the values set for the algorithm). However, if a nuanced or qualitative consideration of the DSM matrix is needed (for example to zoom in on a specific activity or cluster of activities), manual interpretations based on expert judgement can be more applicable to help in structuring and analysing the matrix.

A more detailed elaboration of this activity can be found in Section 4 and Section 5.

4 Constructing the DSM matrix and mapping of interdependencies

In this section, we elaborate on how the DSM matrix used to achieve our research objectives was constructed, as well as shed light on the longlist of interdependencies obtained through our analysis.

4.1 System breakdown structure

The System Breakdown Structure (SBS) should be seen as a list of unique building blocks with which the offshore energy system can be "built". The SBS is structured per discipline (e.g. electricity system, hydrogen system) to create an overview. By combining the separate (sub)systems, various system configurations can be built.

After drafting the SBS as a list of building blocks, an Asset Breakdown Structure will follow. An Asset should be seen as a unique 'copied out' version of a building block system. The ABS determines where these building blocks will be placed, how many of the building blocks are already/will be realized, and whether exceptions and modifications should be applied to the 'typical' building blocks. Systems are thus functional/conceptual objects and assets are physical/geographical objects. Figure 8 below shows the interrelationship between the SBS, configuration and ABS. In this study we only consider *systems* and not their real-world *asset* versions. This implies that the insights gained are of a more abstract nature but can (often) be translated to situations in which the actual asset plays a role.

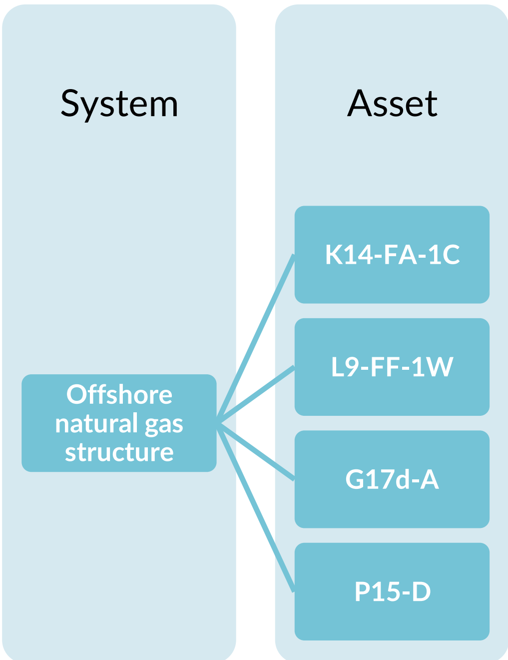

Figure 8: Interrelationship between SBS, configuration and ABS

The System Breakdown Structure considered in the project is shown below in Figure 9 (a-d). The level of detail is limited to subsystems. A higher level of detail, the so-called component level, is partially added to provide examples of underlying components that may be in scope of these subsystems.

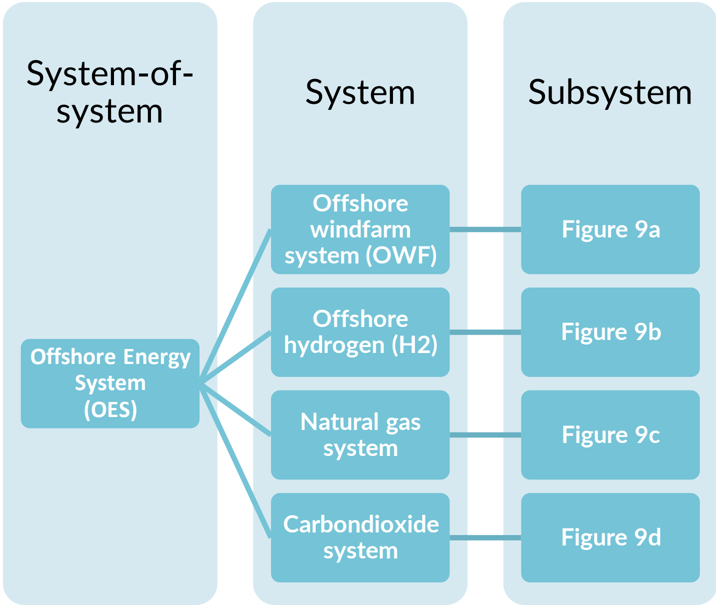

Figure 9: Overview of system decomposition for NSE

SYSTEMS		SUBSYSTEMS		Examples of components (level of detail is beyond the scope of this study)
OWF	**Wind farm E-supply**	EPROD	**E production**	Wind turbine
				Inter-array
		ECONV	**E conversion**	OHVS AC/AC (transformer, switch gear)
				AC-HVDC (transformer, convertor)
		ESTRUC	**E system structure**	Island
				New platform
		ETRANS	**E transport**	Export sea cable AC or DC
				Offshore Interconnection cable (DC)
		EGRID	**Onshore E grid connection**	Onshore high voltage substation (AC/AC or DC/AC)

Figure 9a: System decomposition for offshore wind farms (OWF)

SYSTEMS		SUBSYSTEMS		Examples of components (level of detail is beyond the scope of this study)
H2	**Hydrogen production**	H2CONV	**PtH2 conversion**	Power supply: AC-DC conversion (rectifiers&transformers)
				Water system: desalination & purification unitt, demi water
				Cooling sytem
				Purification system: H2 scrubber, deoxider and drying unit
				O2 by-product equipment (production, storage, compression, transportation)
				Electrolyser
				Local H2 storage
				backup E (?)
		H2STRUC	**H2 system structure**	Island
				New/refit platform
		H2TRANS	**H2 transport**	H2 compressor
				Offshore H2 pipeline
				Offshore H2 interconnection pipeline
				Offshore H2 storage (resevoir, storage equipment, compressor, ...)
		H2ADTRANS	**Admixed H2 transport**	NG-H2 blending equipment
				Offshore NG-H2 blend interconnection pipeline
				Offshore NG-H2 blend pipeline
		H2GRID	**Onshore H2 grid connection**	Onshore H2 terminal
				Onshore NG-H2 blend terminal

Figure 9b: System decomposition for Hydrogen production (H2)

SYSTEMS		SUBSYSTEMS		Examples of components (level of detail is beyond the scope of this study)
NG	Natural gas exploitation	NGEXTR	NG extraction	Offshore natural gas resevoir
				O&G production (extraction and treatment) equipment
				Electric drive train
				Power generator
				Import sea cable
				Onshore high voltage AC transformer station
		NGSTRUC	NG system structure	New/refit platform
		NGTRANS	NG transport	NG compressor
				Offshore NG pipeline
				Onshore NG pipeline

Figure 9c: System decomposition for Natural gas exploitation (NG)

SYSTEMS		SUBSYSTEMS		Examples of components (level of detail is beyond the scope of this study)
CO2	Carbondioxide storage	CO2CAP	CO2 capture	CO2 capturing
				CO2 compressor
				CO2 cleaner
		CO2TRANS	CO2 transport	Onshore CO2 pipeline
				Offshore CO2 pipeline
				Offshore CO2 interconnection pipeline
		CO2STOR	CO2 storage	CO2 resevoir
				CO2 storage equipment
				CO2 compressor
		CO2STRUC	CO2 system structure	New/refit platform

Figure 9d: System decomposition for Carbondioxide Storage (CO2)

4.2 Activity breakdown structure

Asset lifecycle management is the process of managing the lifecycle of an asset "from cradle to grave." As each asset lifecycle consists of similar phases, those phases can be considered universal for the (sub)systems in the SBS. The activities undertaken within a specific phase represent an assumed division of work for each phase. The phases considered in the DSM are shown in Figure 10. The activities per phase indicate the scope of a phase that is considered in this study. For example: the FID of a future (sub)system is assumed to be part of the design phase, the current operation of an existing system (or more correctly put: asset), is part of the O&M phase.

Asset life cycle phase		*The phase includes the following activities:*
OR	Orientation	*Planning & scenario study*
		Concept design (FEED)
		System requirements
DES	Design	*Preliminary design (Epc)*
		Final Investment decision (FID)
		Detailed design (Epc)
CON	Construction	*Procurement (ePc)*
		Production (ePc)
		Transportation (epC)
		Construction (epC)
		Commissioning (epC)
OM	Operation and maintenance	*Operation*
		Maintenance
		Lifetime extension
ABA	Abatement	*Decommissioning*
		Waste disposal

Figure 10: Asset life cycle phases used for the DSM

4.3 Organizational breakdown structure

To complete the type of breakdown structures that were considered relevant in the DSM method for the NSE4 situation, an organizational breakdown structure could be added. Organizations, or stakeholders, can be connected to phases or activities to identify the responsible actors to execute an activity and, in line with the ultimate goal of this study, provide information to other actors responsible for other activities.

The organizational breakdown structure was not developed in the NSE4 project due to resource constraints.

4.4 Resulting set of interdependencies included for the DSM

Taking into account the structure for the DSM as well as building on the information collected through NSE deliverables and interviews with stakeholders, the following long list of interdependencies (as presented in Table 2). One can see that each interdependency has a *source* (origin of information or decision), *target* (recipient of information or decision), *label* (type of information, decision) and motivation (explanation of what the interdependency entails). Note that this list does not include any *precedency* dependencies, which are omitted for ease of interpreting the table (for example, dependencies related to the fact that the operation phase for a system cannot start before it is constructed). Table 2 serves as input for RATIO tooling on the basis of which a DSM matrix is constructed.

Table 2: Longlist of interdependencies included for the DSM matrix

source	target	labels	motivation
CO2_CO2CAP_DES	CO2_CO2STOR_DES	TE	Design of how CO2 is captured (and thus what is captured) -> Design of how CO2 should be stored
CO2_CO2CAP_DES	CO2_CO2TRANS_DES	TE	Design of how CO2 is captured (and thus what is captured) -> Design of how CO2 can be transported
CO2_CO2CAP_OR	CO2_CO2CAP_DES	TE, PRS, SE	Design is based on orientation results
CO2_CO2CAP_OR	CO2_CO2STOR_O&M	TE	CO2 that is captured (its state) -> influences how it should be stored
CO2_CO2CAP_OR	CO2_OR	TE	orientation of the subsystem - influences orientation of the system
CO2_CO2STOR_OR	CO2_CO2STOR_DES	TE, PRS, SE	Design is based on orientation results
CO2_CO2STOR_OR	CO2_DES	TE	Depending on the amount of storage of CO2 needed -> it may be better to design a tailor-made CCS
CO2_CO2STOR_OR	CO2_OR	TE	orientation of the subsystem - influences orientation of the system
CO2_CO2STRUC_DES	CO2_CO2CAP_DES	TE	Design of the platform for CCS influences the design of the capture system for CSS
CO2_CO2STRUC_DES	CO2_CO2STOR_DES	TE	Design of the platform for CCS influences the design of the storage equipment
CO2_CO2STRUC_DES	CO2_CO2TRANS_DES	TE	Design of the platform for CCS influences the design of transport for CSS
CO2_CO2STRUC_OR	CO2_CO2STRUC_DES	TE, PRS, SE	Design is based on orientation results
CO2_CO2STRUC_OR	CO2_OR	TE	Orientation of the subsystem - influences orientation of the system
CO2_CO2TRANS_DES	CO2_CO2STOR_DES	TE	Design of the pipelines (pressure, temperature) -> input for the design of how CO2 is stored
CO2_CO2TRANS_OR	CO2_CO2TRANS_DES	TE, PRS, SE	Design is based on orientation results
CO2_CO2TRANS_OR	CO2_OR	TE	Orientation of the subsystem - influences orientation of the system
CO2_CON	OES_DES	TE	otal lead time of system development is sum of lead time OR, DES, CON. otal lead time determines when CO2 can be realized as part of the OES ystem
CO2_DES	CO2_CO2CAP_OR	TE	Design of the CO2 system -> influences orientation of the capture system
CO2_DES	CO2_CO2STOR_OR	TE	Design of the CO2 system -> influences orientation of the storage system
CO2_DES	CO2_CO2STRUC_OR	TE	Design of the CO2 system -> influences orientation of the capacity system
CO2_DES	CO2_CO2TRANS_OR	TE	Design of the CO2 system -> influences orientation of the transport system

CO2_DES	H2_DES	TE	To produce blue hydrogen, CCS is needed, meaning that the design for CS influences the design for H2
CO2_DES	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. otal lead time determines when CO2 can be realized as part of the OES ystem
CO2_O&M	H2_O&M	TE	The amount of CO2 that is stored influences the degree to which blue hydrogen production can take place
CO2_O&M	NG_CON	TE	TE Stacking of current and future business models of existing platforms lectrified natural gas production, power to gas, carbon storage) --> creased value proposition of platform electrification --> reduced vestment risks for platform operator.
CO2_OR	CO2_DES	TE, PRS, SE	Design is based on orientation results
CO2_OR	H2_OR	TE	To produce blue hydrogen, CCS is needed, meaning that the orientation for CCS influences the orientation for H2
CO2_OR	NG_ABA	TE	Feedback loop TE - the orientation of whether CCS is pursued may influence how the natural gas platforms are abated
CO2_OR	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. otal lead time determines when CO2 can be realized as part of the OES ystem
CO2_OR	OES_OR	TE	To what extent CCS is used influences the costs of the associated OES, nd thus its system-level optimization orientations
H2_ADTRANS_DES	H2_H2CONV_DES	TE	TE Clarity on admix volumes in a specific pipeline is required before the esign of the electrolyser can be finalized
H2_ADTRANS_OR	H2_ADTRANS_DES	TE, PRS, SE	Design is based on orientation results
H2_ADTRANS_OR	H2_OR	TE	Orientation of the subsystem - influences orientation of the system
H2_CON	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when H2 can be realized as part of the OES system
H2_CON	OWF_EGRID_OR	TE	TE H2 production volume -> will alleviate offshore grid congestion
H2_CON	OWF_OR	TE	TE H2 production -> support deployment of ow
H2_DES	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when H2 can be realized as part of the OES system
H2_H2CONV_DES	H2_H2CONV_O&M	TE	TE BOP can be pooled/concentrated = reduce operational flexibility with regards to partial load efficiency
H2_H2CONV_DES	H2_H2TRANS_DES	TE	TE PtH2 capacity design = input H2 infrastructure design
H2_H2CONV_O&M	CO2_CO2CAP_O&M	TE	Production of blue hydrogen - > influences CO2 that is captured
H2_H2CONV_O&M	CO2_CO2STOR_O&M	TE	Production of blue hydrogen -> influences that amount of CO2 to be stored
H2_H2CONV_O&M	CO2_CO2TRANS_O&M	TE	Production of blue hydrogen -> influences CO2 that is transported
H2_H2CONV_O&M	H2_H2CONV_DES	TE	TE Operational production strategy = determining design capacity of electrolyser
H2_H2CONV_OR	H2_H2CONV_DES	TE, PRS, SE	Design is based on orientation results
H2_H2CONV_OR	H2_OR	TE	Orientation of the subsystem - influences orientation of the system
H2_H2GRID_OR	H2_H2GRID_DES	TE, PRS, SE	Design is based on orientation results
H2_H2STRUC_OR	H2_OR	TE	Orientation of the subsystem - influences orientation of the system
H2_H2STRUC_OR	OWF_ESTRUC_OR	TE	PRS / TE clarity on possibilities for synergy OWF+H2 assets on island > benefit from system integration benefits of multi-purpose island OWF+H2
H2_H2TRANS_DES	H2_H2CONV_CON	TE	TE H2 infrastructure design = input local H2 storage design, electrolyser capacity design
H2_H2TRANS_OR	H2_H2TRANS_DES	TE, PRS, SE	Design is based on orientation results
H2_H2TRANS_OR	H2_OR	TE	Orientation of the subsystem - influences orientation of the system
H2_H2TRANS_OR	NG_NGTRANS_ABA	TE	The orientation of how H2 is transported, influences the decision made regarding the abatement of pipelines currently in place (different mixtures of NG/hydrogen may differently affect the pipeline materials already used)
H2_O&M	NG_CON	TE	TE Stacking of current and future business models of existing platforms (electrified natural gas production, power to gas, carbon storage) --> increased value proposition of platform electrification --> reduced investment risks for platform operator.
H2_O&M	OWF_O&M	TE, SE	TE Flexible power consumption hydrogen production system --> more flexibility in offshore electricity system. SE the load following operation of hydrogen production system --> reduced curtailment of offshore wind farms --> less installed capacity in theory --> less spatial claim for offshore windfarms.

H2_OR	NG_NGSTRUC_ABA	TE	The orientation of H2 (is it going to be used), influences the decisions made regarding the abatement of natural gas platforms (does everything have to be removed or can things be re-used, extending the lifetime).
H2_OR	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when H2 can be realized as part of the OES system
NG_ABA	CO2_CO2STOR_OR	TE	TE The amount of gas platforms that will be decommissioned influences how much CO2 can be stored in re-used offshore NG reservoirs through repurposing old OG platforms
NG_ABA	CO2_OR	TE	TE The O&G system with all its assets that can remain after ending NG production determines the decisions to made for the CCS system
NG_CON	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when NG electrification can be realized as part of the OES system
NG_DES	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when NG electrification can be realized as part of the OES system
NG_NGEXTR_OR	NG_NGEXTR_DES	TE, PRS, SE	Design is based on orientation results
NG_NGSTRUC_ABA	CO2_CO2STRUC_DES	TE	The abatement of the natural gas platforms influences the design of the structure of the platform for CCS
NG_NGSTRUC_ABA	CO2_CO2STRUC_OR	TE	The abatement of the natural gas platforms -> influences the orientation of the CCS structure
NG_NGSTRUC_ABA	CO2_DES	TE	The abatement of the existing gas production platform and structure -> influences the CCS design (re-using existing infrastructure where possible)
NG_NGSTRUC_O&M	NG_NGEXTR_DES	TE	TE Platform size and available space = setting the constraints for design of electrified system (cable connection + backup E with GT/batteries/.. on platform, with/without satellite platform, etc)
NG_NGSTRUC_OR	NG_NGSTRUC_DES	TE, PRS, SE	Design is based on orientation results
NG_NGTRANS_ABA	CO2_ABA	TE	TE The abatement of the pipelines (re-use, building new pipelines) influences the costs of the abatement of the pipelines used for CO2
NG_NGTRANS_ABA	CO2_CO2STOR_CON	TE	TE Inside in time lag between reservoirs coming available for storage of CO2 --> clarification on possible timing of project development and --> increased awareness of cooperation conflict.
NG_NGTRANS_ABA	H2_ADTRANS_OR	TE	TE Increased transparency of offshore pipeline and forecasts own goals transport profiles from main trunk line operators --> more accurate annual transport profile estimates of the future --> ability for design and refit of current pipelines.
NG_NGTRANS_ABA	H2_H2TRANS_DES	TE	TE Capacity of existing gas pipelines = input for design retrofitted H2 infrastructure SE quantify reduced impact on ecology by reuse of existing natural gas infrastructure for hydrogen transport --> added value for society and gas infrastructure operators. TE quantify reduced costs by reuse of existing natural gas infrastructure for hydrogen transport --> added value for gas infrastructure operators. TE Pipeline integrity analysis via inspection is input to design decisions to ensure safety of reused pipelines. Design decisions influence costs and therefore the feasibility of projects.
NG_NGTRANS_ABA	H2_H2TRANS_OR	TE, PRS	PRS decision on priority CO2 transport through reused pipelines over hydrogen transport due to relatively high share of CO2 transport costs in the overall unit technical costs for CO2 storage and the technical requirements needed for CO2 --> clarity on re-purpose of current natural gas infrastructure; TE Available & suitable gas pipelines = input for decision retrofit vs new H2 infrastructure; TE Increased transparency of offshore pipeline and forecasts own goals transport profiles from main trunk line operators --> more accurate annual transport profile estimates of the future --> ability for design and refit of current pipelines."
NG_NGTRANS_CON	CO2_CON	TE	Construction of the natural gas transport systems influences the construction of the CO2 system
NG_NGTRANS_O&M	H2_ADTRANS_CON	TE	TE Inside in time lag between pipeline infrastructure coming available for admixed transport of H2 --> clarification on possible timing of project development and --> increased awareness of cooperation conflict.
NG_NGTRANS_O&M	H2_H2TRANS_CON	TE	TE State (quality) of NG pipeline infrastructure ->limit the need to build new H2 transport pipeline, reducing cost TE Inside in time lag between pipeline infrastructure coming available for

			transport of H2 --> clarification on possible timing of project development and --> increased awareness of cooperation conflict.
NG_NGTRANS_OR	NG_NGTRANS_DES	TE, PRS, SE	Design is based on orientation results
NG_O&M	NG_ABA	TE	TE Lifetime extension of O&G production location = additional revenue for O&G system operator
NG_O&M	NG_CON	TE	TE rapid approach of ending production date (due to relatively low gas remaining in place and/or end of permits) can lead to negative business case for platform electrification due to inability to recover initial investments. TE Stacking of current and future business models of existing platforms (electrified natural gas production, power to gas, carbon storage) --> increased value proposition of platform electrification --> reduced investment risks for platform operator.
NG_OR	NG_ABA	TE	Prolonged NG exploitation delays NG abatement
NG_OR	NG_DES	TE, PRS, SE	Design is based on orientation results
NG_OR	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when NG electrification can be realized as part of the OES system
OES_DES	CO2_CO2TRANS_OR	TE	Decide on the operators of the pipelines (public vs. private)
OES_DES	H2_ADTRANS_OR	TE	Decide on the operators of the pipelines (public vs. private)
OES_DES	H2_H2TRANS_OR	TE	Decide on the operators of the pipelines (public vs. private)
OES_DES	H2_OR	PRS, TE	PRS design longer term vision on the development of H2 transport and storage infrastructure --> alignment and integration of ongoing commercial offshore hydrogen production initiatives in the Netherlands and the wider North Sea region. PRS development International H2 infrastructure outlook --> exploration and exploitation of synergies between international projects --> reduction of total system costs. PRS considering not only economics, but also security of supply, human capital, etc. PRS Include onshore and international in scope (in terms of demands, capacities of pipelines, and industrial areas) TE Distance to shore influences transport modality options and decisions to bring energy to shore (AC/DC, H2 and other H2 carriers) - decision on transport determines offshore conversion needs.
OES_DES	OWF_OR	TE, PRS	TE Distance to shore influences transport modality options and decisions to bring energy to shore (AC/DC, H2 and other H2 carriers)- decision on transport determines offshore conversion needs. PRS considering not only economics, but also security of supply, human capital, etc.
OES_O&M	H2_OR	TE	TE increased insight the revenue uncertainty on long-term H2 product demand reduces final investment decision uncertainty and thus investment risks.
OES_O&M	NG_NGEXTR_CON	TE	TE establishment of integrated power network between gas platforms --> reduced electricity infrastructure development costs --> reduced energy system costs.
OES_OR	CO2_OR	TE	TE Orientation of entire Dutch energy system - > influences the orientation of the CCS offshore (for example in harmony with a platform to be electrified) TE Adding system value creation to single actor return on investment increases likelihood of new energy technology development (=CCS) on the North Sea
OES_OR	NG_OR	TE, PRS	TE Adding system value creation to single actor return on investment increases likelihood of new energy technology development (=platform electrification) on the North Sea. PRS global energy trade and geopolitics with regards to NG in current and envisioned future OES determine prolonged and new NG exploitation on the North sea.
OES_OR	OWF_OR	TE	Orientation of entire system - > influences the orientation of OWFs TE Adding system value creation to single actor return on investment increases likelihood of new energy technology development (offshore wind) on the North Sea
OWF_CON	H2_DES	TE	TE OWF system construction = trigger for PtH2 system construction
OWF_CON	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when OWF can be realized as part of the OES system

OWF_DES	H2_H2CONV_DES	TE	TE design choices wind farm operational electricity load profile OWF = design choices operational profile electrolyser
OWF_DES	H2_H2STRUC_DES	TE	TE size of ow -> structure design profitability e.g. 2.5GW ow makes more profitable island
OWF_DES	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when OWF can be realized as part of the OES system
OWF_ECONV_OR	OWF_ECONV_DES	TE, PRS, SE	Design is based on orientation results
OWF_ECONV_OR	OWF_OR	TE	orientation of the subsystem - influences orientation of the system
OWF_EGRID_DES	OWF_OR	TE	The orientation for new off shore energy is highly dependent on how the onshore grid is designed (whether it can manage the load of energy)
OWF_EGRID_OR	OWF_EGRID_DES	TE, PRS, SE	Design is based on orientation results
OWF_EGRID_OR	OWF_OR	TE	Orientation of the subsystem - influences orientation of the system
OWF_EPROD_DES	H2_H2CONV_DES	TE	TE Volume and profile of OWF electricity = input backup electricity generation design
OWF_EPROD_O&M	H2_H2STRUC_O&M	TE	TE Operation WF = input for the operation of the electrolyser
OWF_EPROD_OR	OWF_EPROD_DES	TE, PRS, SE	Design is based on orientation results
OWF_EPROD_OR	OWF_OR	TE	Orientation of the subsystem - influences orientation of the system
OWF_ESTRUC_OR	H2_H2STRUC_OR	TE, PRS	PRS / TE clarity on possibilities for synergy OWF+H2 assets on island > benefit from system integration benefits of multi-purpose island OWF+H2
OWF_ESTRUC_OR	OWF_OR	TE	Orientation of the subsystem - influences orientation of the system
OWF_ETRANS_DES	H2_H2CONV_DES	TE	TE Volume and profile of OWF electricity = input backup electricity generation design
OWF_ETRANS_OR	OWF_ETRANS_DES	TE, PRS, SE	Design is based on orientation results
OWF_ETRANS_OR	OWF_OR	TE	Orientation of the subsystem - influences orientation of the system
OWF_O&M	CO2_CO2STOR_O&M	TE	The degree to which platforms are electrified influences the degree to which the compression, conditioning and monitoring of CO2 can take place
OWF_O&M	OWF_OR	TE	TE More flexibility in offshore electricity system --> better market conditions for variable renewable energy sources.
OWF_OR	H2_H2CONV_OR	TE	TE Available electricity qualities + load profile = power supply choices RES + back-up Electricity
OWF_OR	OES_DES	TE	Total lead time of system development is sum of lead time OR, DES, CON. Total lead time determines when OWF can be realized as part of the OES system

Based on the longlist of interdependencies, the following DSM matrix as illustrated in Figure 11 can be obtained (clustered based on systems). As explained, the sequencing and clustering of this matrix can be altered to fit interpretation and analysis needs.

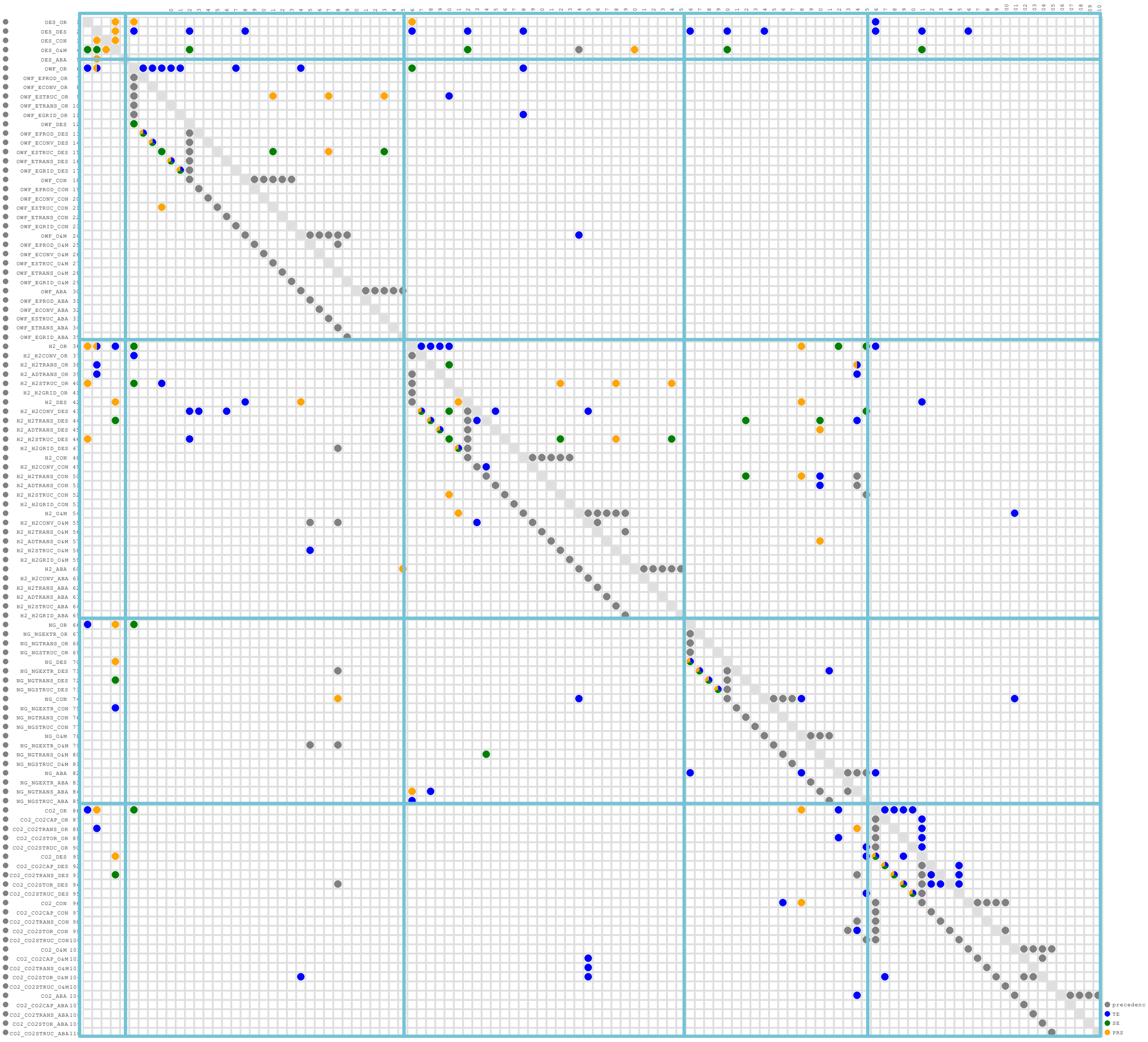

Figure 11: Resulting DSM matrix for NSE (clustered based on systems)

5 Results generated for WP1 and WP7

The clustering and sequencing algorithm would ideally require value judgements and accompanying weighing of information dependencies. The authors did not consider themselves sufficiently informed to make those value judgements and more intensive stakeholder involvement possibilities were constrained by the resources available. Therefore, a case-based interpretation approach was chosen to illustrate the usefulness of the DSM method and provide both the techno-economic hub work (WP1) and roadmap (WP7) with examples of system integration challenges and opportunities based on the DSM output.

To this end, the initial DSM is generated according to an intuitive order of activities: each system-based activity is grouped together based on: [system] [subsystems] [chronological phases] (see Table 3).

Table 3: the intuitive order of activities as provided in the DSM.

Order of activities in DSM
OES_OR
OES_DES
OES_CON
OES_OM
OES_ABA
OWF_OR
OWF_subsystem1_OR
OWF_subsystem2_OR
…
OWF_DES
OWF_subsystem1_DES
…
H2_OR
NG_OR
CO2_OR

The manually generated DSM allowed for an intuitive search for clear case studies of information interdependencies between (sub)system-specific activities while respecting the asset lifecycle-based order of activities: e.g. a design activity need to be completed before a construction activity commences.

5.1 Interpretations for hub development

Research questions 1 and 2 are central to this WP1 interpretation:

- What interdependencies exist between activities to support the development of offshore energy systems in the North Sea Area?
- Based on the interdependencies mapped, what lessons can be learned in terms of system integration for offshore energy systems in the North Sea Area (WP1)

The first research question is answered in Section 4.4. The second research question is answered below.

Insights: increased understanding of system integration complexity via four cases

The DSM-based analysis yields many results from which five key insights, described as *cases of interdependencies*, are identified that illustrate system integration challenges on the North Sea. The cases demonstrate how this interdependency analysis method can be used to support the decision-making within, and between, the relevant activities.

The first case relates to understanding the information flows between the offshore wind farms, centralized offshore hydrogen production and natural gas platform electrification.

In the second case and third, the consequences of prolonged natural gas platform operation on the availability of infrastructure for re-use purposes is brought forward, as well as the conflicting interests of infrastructure for hydrogen, admixing or CO_2 on the same existing natural gas infrastructure.

Case four and five discuss the interdependencies of investment decisions regarding offshore electrolysers and CO_2 storage on other activities on the North Sea and on shore.
The sum of all (inter)dependencies for each individual activity makes explicit what is needed to complete that activity successfully. A selection of information dependencies is presented in the cases below. The complete information dependencies between activities is provided in Section 4.4.

The systems and activities under consideration are generic and not location-specific. To understand which of the five cases above are relevant for Hub West, Hub East and Hub North, we compare the storylines and characteristics of the different hubs to the different interdependency cases in Table 4.

Table 4: Overview of the five cases identified and their relevancy to the hubs in NSE

		Case 1 OWF required for H2 production & NG electrification	Case 2 Lifetime extension of natural gas exploitation platforms blocks reuse of infrastructure	Case 3 Clarity on reuse purposes NG pipeline to start CO2 or H2 admixing refurbishment	Case 4 Offshore electrolysers FID	Case 5 CO2 storage demand and FID
Hubs and their storylines	<u>**Hub West**</u> *P2G on a sandy island.* *Dedicated P2G on multiple platforms.* *Dedicated P2G on multiple platforms and flexible P2G at single platforms.*	**Relevant**, though only for the production of H2 (platform electrification through offshore wind electricity for gas production and CCS only is not considered).	**Not relevant** (platform electrification through offshore wind electricity for gas production and CCS only is not considered)	**Relevant**, as existing pipelines are considered in the modes of transport,	**Relevant**	**Highly relevant** (storage potential for CO2 is very high)
	<u>**Hub East**</u> *Dedicated P2G on a sandy island.* *Flexible P2G on a sandy island.* *P2G on multiple platforms.*	**Relevant**, both for H2 production and NG electrification	**Not relevant**	**Relevant**, though only for admixing in existing pipelines (no CO2 transport)	**Relevant**	**Not relevant**
	<u>**Hub North**</u> *Focus on re-use of the existing infra.* *Focus on making a network of existing infra.* *New pipelines.*	**Relevant**, both for H2 production and NG electrification	**Highly relevant** – electrification of existing platforms will occur in an early stage	**Highly relevant** (focus on re-use of existing infra is one of the storylines)	**Relevant**, as large scale hydrogen will be produced on multiple platforms	**(Probably) not relevant**, only CO2 transportation (connection to hub West).

Case 1: OWF required for H2 production & NG electrification (Figure 12)

To enter the operational phase, a green hydrogen production system requires electricity (from offshore wind farms) to power the electrolysers and auxiliary subsystems. And as a prerequisite to access that renewable power, the electricity transport infrastructure needs to be in operation. This implies a sequence in asset commissioning on the North Sea.

Operation of electrified natural gas platforms have similar dependencies: the need for renewable power can be fulfilled if both the OWF and the electricity transport infrastructure is operational. To this end, both the hydrogen production system and the natural gas production systems depend on the timely commissioning of the complete offshore wind farm system and power transport system.

The vicinity of supply, transport and demand systems plays a major role in the possibility to integrate OWF, H_2 and NG systems: the *decisions on wind farm development areas* (part of the OWF orientation phase) determine the extent to which integration with hydrogen production systems or gas platforms is attainable. The *power demand, timing and feasibility* of platform electrification, hydrogen production and CO_2 storage subsequently determines the (industrial) need to utilize the power on-site at the North Sea.

And the local power ‘consumption’ needs *influence the need for electrical infrastructure* to shore and thus the lead-time of the OWF system.

#	Dependency explanation
1	OWF_ESTRUC_OR→ H2_H2STRUC_OR:*(PRS/TE) clarity on possibilities for synergy between the OWF and H2 assets on an island →results in system integration benefits of a multi-purpose island with OWF and H2*
2	OWF_OR → NG_OR: *(SE) If OWFs are connected to the platform to support electrification, NG activities can be decarbonized. OWF spatial planning enables electrified NG extraction.*
3	OWF_ETRANS+O&M → OWF_EPROD_O&M: *An OWF can start its operations when the cable is in operation*
4	i) OWF_EPROD_O&M → H2_H2CONV_O&M and OWF_ETRANS_O&M → H2_H2CONV_O&M: *PtH2 assets can start operations when both an OWF and the cable are in operation* ii) OWF_EPROD_O&M → H2_H2STRUC_O&M: *(T) Operations of the OWF are input for the electrolyzer*
5	OWF_EPROD_O&M → NG_NGEXTR_O&M and OWF_ETRANS_O&M → NG_NGEXTR_O&M : *Electrified natural gas extraction can start operations when the both the OWF and the cable are in operation*

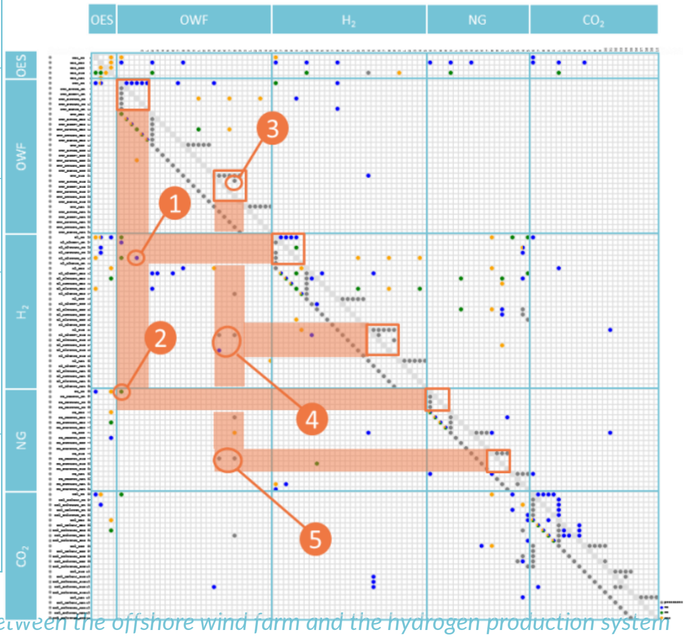

Figure 12: The DSM containing interdependencies between the offshore wind farm and the hydrogen production system and natural gas platforms respectively (case 1)

Case 2: Lifetime extension of natural gas exploitation platforms blocks reuse of infrastructure (Figure 13)

The third case relates to the required decision *<u>when</u> to re-use existing natural gas pipelines, wells and platforms.*

The extent to which natural gas extraction from wells on the North Sea is continued in the future determines to a large extend the possibility of re-using those assets for new purposes: H_2 or CO_2 production and/or storage and transport to shore or neighboring countries. The timing of pipeline, well and/or platform asset repurposing therefore depends on the natural gas production forecasts, permits to operate and (inter)national policies that set natural gas production targets.

Extension of NG exploitation timelines therefore delays repurposing pipelines, wells or platforms and consequentially delays the commissioning date of CO_2 storage and/or H_2 production systems that depend on to-be-repurposed pipeline infrastructure. The effort to benefit from the merits offered by re-using natural gas assets may thus lead to a slower energy transition on the North Sea.

#	Dependency explanation
1	OES_OR → NG_OR: PRS *Global energy trade and geopolitics with respect to NG in current and envisioned future OES determines prolonged and new NG exploitation on the North sea.*
2	NG_ABA → CO2_OR: TE *The O&G system with all its assets that can remain after ending NG production determines the decisions to made for the CCS system.*
3	NG_OR à NG_ABA: TE *Prolonged NG exploitation delays NG abatement*
4	NG_NGEXTR_ABA → CO2_CO2STOR_CON: *The natgas extraction assets need to stop producing before it can be repurposed into CO2 storage site* NG_NGSTRUC_ABA → CO2_CO2STRUC_CON: *The abatement of the natural gas platforms influences the construction (planning) of the structure of the platform for CCS*
5	NG_NGTRANS_ABA → H2_H2TRANS_CON: *The operation of the natgas pipeline need to be stopped before the natgas pipeline can be repurposed to H2 pipeline* NG_NGSTRUC_ABA → H2_H2STRUC_CON: *The natgas extraction assets need to stop producing before it can be repurposed into a dedicated H2 conversion asset*

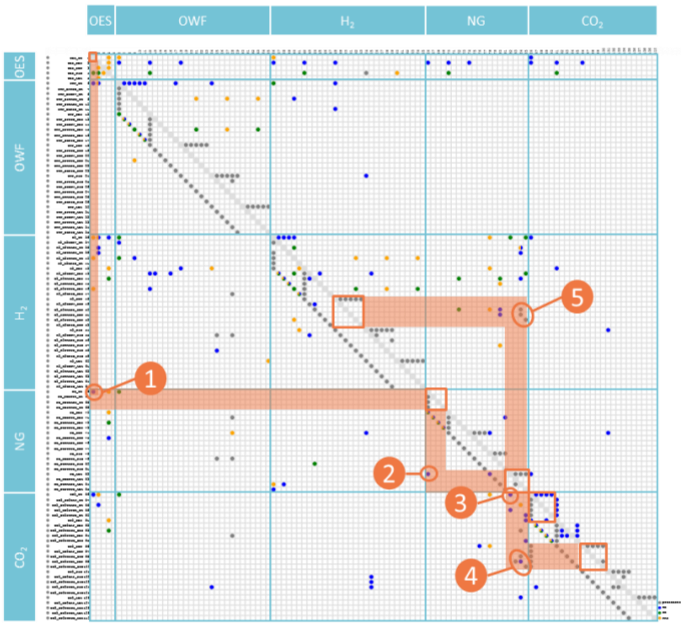

Figure 13: The DSM containing interdependencies relevant for the re-use of existing natural gas pipelines, wells and platforms (case 2)

Case 3: Clarity on reuse purposes NG pipeline to start CO2 or H2 admixing refurbishment (Figure 14)

The third case relates to the required decision for <u>which purpose</u> *existing natural gas pipelines are to be re-used*: CO_2, pure hydrogen or admixed hydrogen. The decision on how to repurpose the infrastructure is inevitable, as only one new role can be assigned to the pipelines. *Pipelines for CO2, H2 or admixed hydrogen require different pipeline performance characteristics*, meaning that NG pipelines may be reused for either CO2, H2 or H2 admixing purposes, or may not be suitable for re-use. Therefore, the orientation, design and construction of CO_2, H_2 or admixed H_2 transport infrastructure depends strongly on how, when and which pipelines currently in use for natural gas transport are abated and whether that *NG pipeline performance characteristics are such that the pipeline can be modified for a specific type of reuse*.

The interdependencies regarding this re-use decision is illustrated in the DSM: Information regarding the NG pipeline performance characteristics and abatement timelines flows from the natural gas operation & maintenance phase and abatement phase towards the CO_2, H_2 or admixed H_2 orientation, design and construction phases. And decisions on preferred *re-use purposes are guided by offshore energy system level policies.*

#	Dependency explanation
1	i) NG_NGTRANS_ABA → H2_ADTRANS_OR: TE *Increased transparency of offshore pipeline and forecasts own goals transport profiles from main trunk line operators --> more accurate annual transport profile estimates of the future --> ability for design and refit of current pipelines.* ii) NG_NGTRANS_ABA → H2_H2TRANS_OR: TE *Available & suitable gas pipelines = input for decision retrofit vs new H2 infrastructure. Increased transparency of offshore pipeline and forecasts own goals transport profiles from main trunk line operators --> more accurate annual transport profile estimates of the future --> ability for design and refit of current pipelines.* iii) NG_NGTRANS_ABA → H2_H2TRANS_DES: TE *Capacity of existing gas pipelines = input for design retrofitted H2 infrastructure*
2	i) NG_NGTRANS_ABA → CO2_CO2TRANS_DES: TE *Pipeline integrity analysis via inspection is input to design decisions to ensure safety of reused pipelines. Design decisions influence costs and therefore the feasibility of projects. Quantify reduced costs by reuse of existing natural gas infrastructure for CO2 transport --> added value for gas infrastructure operators.* ii) NG_NGTRANS_ABA → CO2_CO2TRANS_OR: TE, PRS *Available & suitable gas pipelines = input for decision retrofit vs new CO2 infrastructure Decision on priority CO2 transport through reused pipelines over hydrogen transport due to relatively high share of CO2 transport costs in the overall unit technical costs for CO2 storage and the technical requirements needed for CO2 --> clarity on re-purpose of current natural gas infrastructure*
3	OES_DES → CO2_OR: PRS OES_DES → H2_OR: PRS *Design longer term overarching governmental vision on the development of CO2 and H2 transport and storage infrastructure. Dutch target-setting for longer term investment security for offshore CO2 and H2 transport and storage investments. Development International CCS H2 infrastructure outlook.*

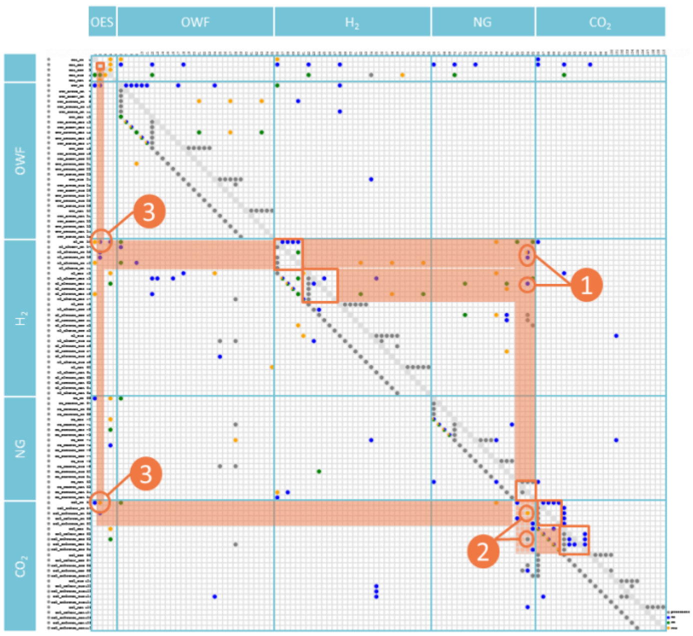

Figure 14: The DSM containing interdependencies relevant for the repurposing of NG pipelines for CO2 or H2 admixing (case 2)

Case 4: Final investment decisions (FID) for offshore electrolysers (Figure 15)

The design phase activities of the hydrogen conversion subsystem includes making the final investment decision (FID). The FID is commonly made only with a positive cost-benefit balance for its owner. The *information inputs required for a FID by that H2 conversion system owner are* originating from a wide range of activities on the North Sea, amongst which:

- The design of the offshore wind farm that provides the power supply profile that should fit the power demand profile of the envisioned electrolyser design. The designed power profile of the OWF on its turn depends on decisions made within the design phase of the wind turbine generators and the electricity conversion and transportation assets.

- The power production and transportation design activities will also indicate the possible design options to add back-up electricity capacity solutions, as part of the H2 system design, to maximize the operational hours of the hydrogen system.
- Increased insight in the revenue uncertainty on long-term H2 product demand, through future energy system simulation and scenario studies, can improve the understanding of uncertainty and thus investment risks and facilitate the FID.
- Production locations of wind farms leads to clarity on preferred offshore structure design (e.g. island, new platform, re-used platform), multi-purpose land use options and the implied investment costs and ease of phased investment in electrolysis capacity.

#	Depedency explanation
1	OWF_OR → H2_OR: *(SE) If OWFs are connected to the platform to power centralized electrolyser, H2 activities can be enabled. OWF spatial planning influences H2 orientation. Connecting OWF and H2 systems may lead to high investment costs in infrastructure if spatial orientations are suboptimal.*
2	i) OWF_ETRANS_DES → H2_H2CONV_DES: (T) The volume and profile of OWF electricity generation influence the backup electricity generation design ii) OWF_CON → H2_DES: TE OWF system construction is a trigger for PtH2 system design (and subsequent FID).
3	OWF_DES → H2_H2CONV_DES: *(T) design choices wind farm operational electricity load profile OWF = design choices operational profile electrolyser.* OWF_EPROD_DES → H2_H2CONV_DES: *(T) Volume and profile of OWF electricity = input backup electricity generation design*
4	OES_O&M → H2_OR: *(TE) increased insight the revenue uncertainty on long-term H2 product demand in the future energy system as a whole reduces FID uncertainty and thus investment risks.*

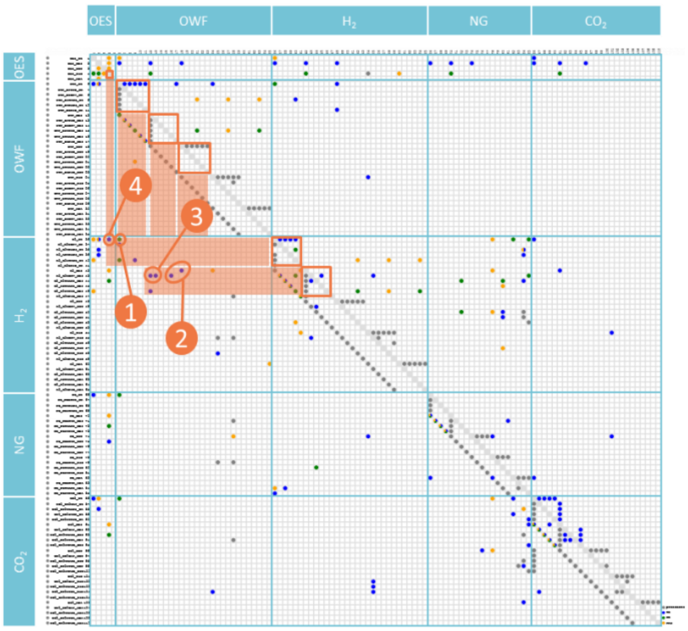

Figure 15: The DSM containing interdependencies for the FID of the hydrogen electrolyser decision (case 4)

Case 5: Final investment decisions (FID) for CCS (Figure 16)

The fifth case concerns the interdependencies that exists for making a final investment decision on the development and installation of CO2 capture and storage systems. One can see for Figure Y that the decision to invest in CSS (as part of the design phase of CO2) serves as the starting point for investments in the individual subsystems (1). This final investment decision takes into account the market demand for CO2 storage: stakeholders should commit to the storage of CO2 undergrounds to make an investments for the development and installation of a new CO2 capture and storage system worthwhile. It should therefore be apparent how much CO2 will be stored over time to motivate this decision making. Once the final investment decision is made, the investments for its subsystems (e.g. transportation via pipelines, platform structure) can start, taking these parameters into account.

On the other hand, we see that the design parameters of the individual subsystems also influence whether a final investment decision for the entire CCS system can be made (2). For example, the design parameters for CO2 storage or CO2 transportation provide input to the 'value' of the CCS system to potential market stakeholders. For instance, the parameters set for CO2 storage influence the amount of CO2 that can be stored for the system. This in turn influences whether the final investment decision for the CCS system as whole can be made.

As a result of these interdependencies, a classical *chicken-egg* problem emerges: the final investment decision for the CCS system influences how individual subsystems for the CCS system are to be developed. This final investment decision is dependent on market demand for CO2 storage. However, the parameters for the individual subsystems influence what amount of market demand can be expected, and therefore in turn affect the final investment decision for the CCS system. To break this stalemate, decisions should already be taken on the design parameters for individual subsystems of CCS, whereas (long-term) commitment should be pursued on how much CO2 will be stored by market stakeholders.

#	Depedency explanation
1	CO2_DES -> CO2_CO2STOR_DES; CO2_CO2CAP_DES; CO2_CO2TRANS_DES; CO2_CO2STRUC_DES (*precedence*): *The design (FID) on the system level influences the design of the individual subsystems, providing input for design parameters.*
2	CO2_CO2STOR_DES; CO2_CO2CAP_DES; CO2_CO2TRANS_DES; CO2_CO2STRUC_DES -> CO2_DES (*techno-economic*): *The design of the individual subsystems (how much is stored, pipelines used) influences the final investment decision on system level.*

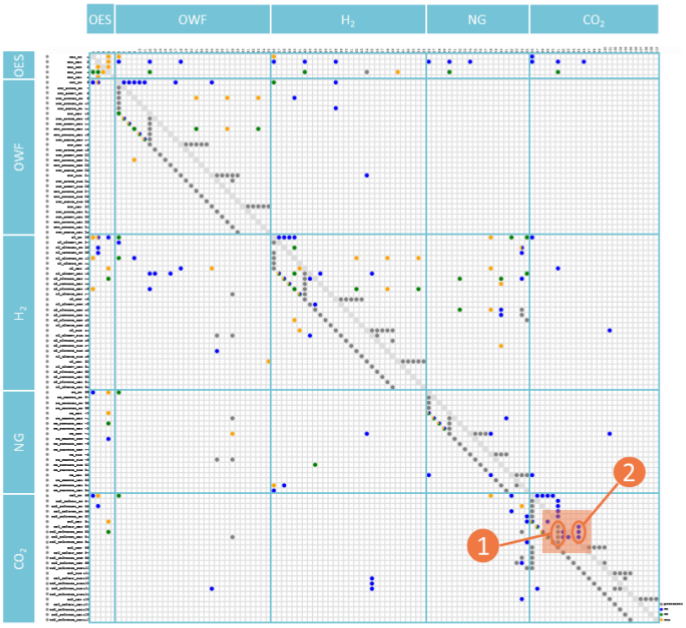

Figure 16: The DSM containing interdependencies for the CO2 storage demand and FID (case 5).

5.2 Interpretations for roadmap development

Research question 3 is central to this WP1 interpretation:

- Based on the interdependencies mapped, what key recommendations can be presented in terms of actions and decisions to be taken to accelerate the development of offshore energy systems in the North Sea Area (WP7)?

Key recommendations to accelerate the development of offshore energy systems

The key recommendations are as follows.

1. Decide early on system integration plans minimizes delays in system developments

System integration can be beneficial when synergies of different systems are exploited. System integration however requires alignment and collaborations which take time and require commitment of multiple stakeholders. Early decisions on where and why SI is desirable and applied are needed: Decisions that may introduce lock-in situations due to SI commitments or deliberate exclusion of SI cannot be evaded entirely. Pushing those decisions forward in time causes delays in the development of the energy system that we cannot afford when working towards climate goals.

Even though the (future) systems at the North Sea are highly interrelated, their timelines towards technological maturity vastly differ. In terms of planning and orientation for future energy systems, certain technologies are not yet fully mature at present, however they should be included in current decision-making to be able to be integrated in the future. An example is the interdependency between the less mature green hydrogen production system and the offshore wind farms, power grid connection and natural gas platforms. This means that in terms of the long-term planning of offshore energy systems for the North Sea, decisions already have to be made which offshore platforms are suitable to support green hydrogen production later on and where new offshore wind farms should potentially be built and connected to those platforms to support the production of green hydrogen.

If systems are to be integrated in the future, a clear development plan and preliminary decisions on how and which systems of the North Sea will be used is essential. Therefore, stakeholders such as spatial planners, energy policy makers and asset providers should already decide now on the application of the different areas of the North Sea in terms of spatial planning and the orientation of offshore wind farms. Consequently, they should decide on what this implies for future system integration: what purpose will each platform have towards system integration? And if systems are not to be integrated, making such a decision explicit reduces uncertainties and thus accelerates the developments of systems on the North Sea as those system developers do not have to align with other systems they potentially need to integrate with.

2. Create clarity on future natural gas extraction policy and asset usage to accelerate the re-use of platforms, wells and pipelines for hydrogen production and carbon storage.

Proceeding towards tangible investment decisions regarding offshore carbon capture storage and hydrogen production activities benefits from reducing uncertainties regarding the reuse potential of current systems. Clarity on two topics can decrease this uncertainty: 1) Dutch and European long-term natural gas extraction policies (e.g. what volumes of natural gas extraction should be considered, and for how long, to support our energy needs?); and 2) which wells (and associated platforms and pipelines) are close to depletion and are therefore potential candidates for re-use in the near future, independent of natural gas policies?

The development and installation of carbon storage or hydrogen production systems, either as new systems or through re-using systems, largely depends on if and/or how the current natural gas systems are to be repurposed. Whether platforms are repurposed however is heavily dependent on Dutch and European policies regarding natural gas extraction: continuing natural gas extraction activities for current platforms (instead of repurposing platforms for different systems), implies that the opportunity or availability of platforms fit for re-use decreases, alongside any pipeline infrastructure.

Energy system stakeholders (energy policy decision makers, infrastructure operators, natural gas asset operators and future hydrogen and CO2 asset operators) should work on defining future NG, H2 and CO2 energy production and storage potential with and without asset re-use over time and thereby connect top-down policy decisions to bottom-up asset capabilities.

3. Shape Dutch intentions and targets for long-term for CO2 storage to support CCS development

Long-term net zero emission targets are impossible without negative emission measures. Yet, investments in the development of CCS systems are dependent on: 1) how much CO2 can be stored underground for a given platform and when storage activities can commence (which in turn is dependent on whether the platform is repurposed or not); 2) the volumes and timing of the supply of CO2 to be stored; and on 3) the Dutch decisions in terms of CO2 storage targets.

Currently, no clear goals are set regarding the amounts of CO2 to be stored underground for the coming years in the Netherlands. As a result, stakeholders are reluctant to invest as uncertainty regarding the definition of CO2 storage contracts is high, which results in the timeline for CSS development to only mature slowly. If quantitative goals for CCS are set for both CO2 capture and storage, it will become more attractive for organizations to proceed with CCS developments. This will help in shaping project timelines towards the installation and use of CCS systems. Therefore, to accelerate the development of CCS systems long-term, policy makers, natural gas operators and project developers for CCS should collaboratively work towards setting realistic goals regarding CO2 storage over time. Communicating these goals early on can further contribute to understanding what, and to what extent, natural gas platforms currently in use can be repurposed.

6 Conclusions and recommendations

In this report, we conducted a first exploration and analysis of the interdependencies that exist for activities to be conducted for the North Sea Energy project, using the Dependency Structure Matrix (DSM) method combined with different clustering and sequencing algorithms. Such an analysis allows for decision makers to make explicit in what order certain decisions and actions should be taken or executed.

Results obtained and general conclusions

Through this analysis, we have first identified five different cases that illustrate various system integration challenges on the North sea:

- The first case relates to understanding the information flows between the offshore wind farms, centralized offshore hydrogen production and natural gas platform electrification.
- In the second case and third, the consequences of prolonged natural gas platform operation on the availability of infrastructure for re-use purposes is brought forward, as well as the conflicting interests of infrastructure for hydrogen, admixing or CO2 on the same existing natural gas infrastructure.
- Case four and five discuss the interdependencies of investment decisions regarding offshore electrolysers and CO_2 storage on other activities on the North Sea and on shore.

The sum of all (inter)dependencies for each individual activity makes explicit what is needed to complete that activity successfully. These findings can be used to support the decision-making within, and between, the relevant activities. Based on the analysis of these five cases, we recommend the following to decision makers in the North Sea Energy project:

1. Decide early on system integration plans to minimize delays in system developments
2. Create clarity on future natural gas extraction policy and asset usage to accelerate the re-use of platforms, wells and pipelines for hydrogen production and carbon storage.
3. Shape Dutch intentions and targets for long-term for CO2 storage to support CCS development

Lastly, we conclude with two important additional findings from our analysis.

- Information dependencies between system-development activities may lead to deliberate decisions to not exploit system integration benefits to prevent delays in activity executions.
- Complete system-level (OES) policy-related information can break information interdependency situations and thus accelerate integrated system developments.

Recommendations and next steps

Next to our limitations, we have also identified a number of recommendations to further improve interdependency analysis for NSE using DSM matrices:

- First of all, the level of detail of information dependencies between activities should be improved to develop a more fine-grained analysis of dependencies between activities on a specific location, focusing on actual (in contrast to theoretical) assets. For our analysis, we were reliant on past deliverables and (time-constrained) interviews with relevant stakeholders to support the identification of interdependencies. Given the scope of NSE, which includes many concurrent stakeholders working on system development, the current set of interdependencies can only be considered as the 'tip of the iceberg'. This set of interdependencies should be expanded on and further detailed to draw additional conclusions or recommendations for supporting off-shore system development. To do so, the information and knowledge of asset owners and stakeholders present and/or needed to develop the systems should be included in the analysis.

- Secondly, the activity interdependency analysis can be extended to include the stakeholders responsible for each activity related to system developments (and if desirable: system integration) on the North Sea as well as value judgements to each information dependency. Due to capacity and time constraints for this research, we were unable to map (concrete) stakeholders to specific tasks or to offer value judgements to specific interdependencies. By adding stakeholders to activities, analyses can be executed to assess which specific stakeholder is involved, when that stakeholder needs to make a decision and/or supply a piece of specified information to another stakeholder, and where joint decision making should be considered between which stakeholders. This can be the basis for valuable insights on what stakeholders to engage or motivate to take charge to accelerate decision making. Alternatively, adding values to independency relations enables stakeholders to prioritize the decisions to be made and information to be communicated: it can help in identifying what interdependencies are critical as opposed to others and thus what decisions should be taken first, particularly in cases many concurrent decisions are to be made. This can significantly speed up decision making and thus contribute towards accelerating offshore systems development.

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