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# Multiple product-project decisions coordination support : application to oil and gas development projects

Meriam Kilani

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Aide à la coordination de décisions multiples  
produit-projet : Application aux projets de  
développement pétroliers et gaziers

Multiple product-project decisions coordination  
support: Application to oil and gas development  
projects

**Thèse de doctorat de l'université Paris-Saclay**

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(Interfaces)

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**Thèse soutenue à Paris-Saclay, le 13 février 2023, par**

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**Titre :** Aide à la coordination de décisions multiples produit-projet : Application aux projets de développement pétroliers et gaziers

**Mots clés :** prise de décision, coordination, interdépendance des décisions, modélisation, scénarios de décision.

**Résumé :** Le défi majeur abordé dans cette recherche concerne la coordination de multiples décisions interdépendantes qui doivent être prises lors du projet, qu'elles soient techniques, financières ou contractuelles. Interdépendance signifie que prendre une décision sans tenir compte des impacts sur les autres décisions peut entraîner une sous-performance, voire des impasses, des itérations et des reprises.

Pour surmonter ce défi, un processus de prise simultanée de décisions multiples a été proposé, en trois blocs : 1/ modélisation du réseau de décisions et formulation du problème multi-décisionnel ; 2/ structuration du problème pour proposer des scénarios pertinents et plausibles assemblés à partir d'alternatives de décisions élémentaires ; 3/ résolution du problème par la sélection et la recommandation de scénarios.

La construction du processus de prise de décisions multiples est basée sur des possibilités diverses pour chaque bloc. Le décideur sélectionne parmi un ensemble de choix possibles pour adapter le processus décisionnel à son contexte précis.

Pour le bloc 1, nous avons d'abord construit un réseau global qui modélise les décisions étudiées et les interdépendances qu'elles peuvent avoir avec d'autres décisions. Nous avons ensuite indiqué que les graphes et les matrices peuvent être utilisés pour répondre à ce besoin. Les deux méthodes permettent d'inclure toutes les décisions et interdépendances du réseau de décision dans un seul modèle, chacune d'entre elles ayant ses avantages et inconvénients, avec une sorte de complémentarité.

Ensuite, pour formuler le problème local de multi-décision, deux approches de clustering basées sur les interactions sont proposées : l'approche descendante (considérant les interdépendances des décisions) et l'approche ascendante (avec un regroupement supplémentaire des décisions basé sur la date d'échéance). Ces deux approches aident à délimiter le périmètre sur un ensemble spécifique de décisions, étant donné qu'il

peut être difficile de considérer tout le réseau de décisions en même temps.

Dans le bloc 2, pour structurer le problème, deux méthodes basées sur des matrices et une autre basée sur des graphes ont été proposées. Ces méthodes offrent la possibilité de générer des scénarios en considérant les critères de compatibilité et de performance, soit séquentiellement (analyse morphologique), soit simultanément (QFD), soit de manière hybride (exploration de graphe). Pour les deux méthodes basées sur les matrices, un algorithme a été proposé pour faciliter l'identification de scénarios plausibles. Quant à la méthode basée sur les graphes, une heuristique plus légère peut être appliquée en temps réel lors d'une réunion de décision.

Enfin, pour résoudre le problème, plusieurs méthodes MCDA ont été répertoriées dans le bloc 3 pour évaluer et sélectionner un scénario recommandé : méthodes d'évaluation absolue, méthodes de comparaison relative par paire, et méthodes de comparaison relative à des points de référence.

Selon les acteurs industriels, un tel processus pourrait améliorer les mécanismes de coordination entre les décisions majeures de leurs projets. Même si les décisions sont interdépendantes, elles ne sont pas souvent considérées comme telles, et le processus que nous proposons permet (selon eux) d'avoir une meilleure vision des décisions à prendre ensemble et des conséquences des choix. Une étude de cas fictive, inspirée de projets réels passés, a été utilisée pour illustrer le processus de coordination multi-décision proposé.

Nous sommes convaincus que notre recherche fournira une base solide pour d'autres études portant sur la coordination de décisions multiples et interdépendantes dans le cadre de projets complexes, même si certaines perspectives académiques et industrielles doivent être abordées.

**Title:** Multiple product-project decisions coordination support: Application to oil and gas development projects  
**Keywords:** decision-making, coordination, Interdependency of decisions, modeling, decision scenarios.

**Abstract:** The major challenge addressed in this research concerns the coordination of the multiple interdependent decisions that must be made during the project, either technical, financial, or contractual. Interdependence means that making one decision without considering the impacts for other decisions may imply some underperformance, or even dead ends, iterations, and rework.

To overcome this challenge, a more adaptable multi-decision-making process has been proposed, consisting of three blocks: 1/ modeling the decision network and formulating the multi-decision problem; 2/ structuring the problem to propose relevant and plausible scenarios assembled from elementary decision alternatives; 3/ solving the problem by selecting and recommending scenarios.

Building the multi-decision-making process is based on multiple possibilities for each block. The decision-maker selects from a set of possible choices to adapt the decision-making process to the precise context.

For block #1, we have first articulated the need to build a global decision network that models the decisions under study and the interdependencies they may have with other decisions. We have then argued that graphs and matrices can be used to fulfill this need. Both methods allow to include all decisions and interdependencies of the decision network in one single model, each of them having its advantages and drawbacks, with a kind of complementarity.

Then, to formulate the local multi-decision problem, two interactions-based clustering approaches are proposed: the top-down approach (considering decision interdependencies) and the bottom-up approach (with an additional due date-based grouping of decisions). Both help to delineate the focus of decision makers on a specific set of decisions, since considering the whole network of decisions at the same time can be challenging.

In block #2, to structure the problem, two matrix-based and one graph-based methods have been proposed. These methods offer the possibility to generate possible scenarios considering compatibility and performance criteria, either sequentially (morphological analysis), simultaneously (QFD), or with a hybrid way (graph exploration). For the two matrix-based methods, an algorithm was proposed to facilitate the identification of plausible scenarios. As for the graph-based method, a lighter heuristic can be applied on live during a decision meeting.

Finally, to solve the problem in block #3, several MCDA methods have been listed for evaluating and selecting a recommended scenario: absolute compensatory methods, relative pairwise comparison methods, and relative comparison to reference point methods.

According to industrial actors, such a process could improve coordination mechanisms between the major decisions of their projects. Even though decisions were interdependent, they were not often considered as such, and our proposed process permits (according to them) to have a better vision of the decisions to be made together and of the consequences of the choices. A fictitious case study, inspired by real past projects, was used to illustrate the proposed multi-decision coordination process.

We are convinced that our research will provide a solid basis for further studies on the coordination of multiple interdependent decisions in complex projects, although there are academic and industrial perspectives that need to be tackled.

# Résumé

Le défi majeur abordé dans cette recherche concerne la coordination de multiples décisions interdépendantes qui doivent être prises lors d'un projet de développement pétrolier et gazier. Interdépendance signifie que prendre une décision sans tenir compte des impacts sur les autres décisions peut entraîner une sous-performance, voire des impasses, des itérations et des reprises. Les enjeux élevés en termes de coûts, de délais, de qualité, de production et de paramètres HSE ont été présentés dans le chapitre 1.

Une question de recherche globale a été identifiée au chapitre 2, à savoir : "Comment aider les décideurs à prendre des décisions multiples de manière coordonnée ?". Pour traiter cette question plus en détail, elle a été divisée en deux sous-questions : 1) "Comment s'assurer que les interdépendances entre les décisions sont correctement gérées ?" 2) "Comment aider les décideurs à prendre des décisions multiples de manière coordonnée et à améliorer la compatibilité de ces décisions ?"

Pour répondre à la question de recherche principale et aux questions de recherche secondaires, une proposition a été proposée à la fin du chapitre 2. Elle consiste à proposer un processus de multi-décision plus adaptable et agile composé de trois blocs : 1/ modélisation du réseau de décisions et formulation du problème multi-décisionnel ; 2/ structuration du problème pour proposer des scénarios pertinents et plausibles assemblés à partir d'alternatives de décisions élémentaires ; 3/ résolution du problème par la sélection et la recommandation de scénarios.

La construction du processus de prise de décisions multiples est basée sur des possibilités diverses pour chaque bloc. En effet, étant donné la diversité des contextes des projets de développement pétrolier et gazier, le processus proposé est un processus à entrées multiples. A chaque bloc, le décideur sélectionne parmi un ensemble de choix possibles pour adapter le processus de décision au contexte précis.

Dans le chapitre 3, nous avons détaillé le premier bloc. Nous avons d'abord construit un réseau global qui modélise les décisions étudiées et les interdépendances qu'elles peuvent avoir avec d'autres décisions. Nous avons ensuite indiqué que les graphes et les matrices peuvent être utilisés pour répondre à ce besoin. Les deux méthodes permettent d'inclure toutes les décisions et interdépendances du réseau de décision dans un seul modèle, chacune d'entre elles ayant ses avantages et inconvénients, avec une sorte de complémentarité.

Ensuite, pour formuler le problème local de multi-décision, deux approches de clustering basées sur les interactions sont proposées : l'approche descendante (considérant les interdépendances des décisions) et l'approche ascendante (avec un regroupement supplémentaire des décisions basé sur la date d'échéance). Ces deux approches aident à délimiter le périmètre sur un ensemble spécifique de décisions, étant donné qu'il peut être difficile de considérer tout le réseau de décisions en même temps.

Il est important de mentionner à ce stade que les deux approches permettent de minimiser les difficultés de gestion des interdépendances et d'augmenter la capacité à coordonner de multiples décisions interdépendantes. Le choix de la meilleure approche est laissé aux décideurs et dépend de plusieurs paramètres tels que : la capacité à évaluer l'interdépendance entre les décisions, la disponibilité des données temporelles, la capacité de l'équipe à gérer plusieurs décisions à la fois, le nombre de décisions pouvant être gérées aisément par les décideurs, la complexité du réseau, la disponibilité des données historiques et du feedback sur les projets, le niveau d'importance de certaines décisions, etc. Les décideurs doivent donc choisir le mode de construction approprié en fonction de leurs propres critères.

Au chapitre 4, nous avons détaillé le deuxième bloc du processus qui consiste à structurer le problème. Deux méthodes basées sur des matrices et une autre basée sur des graphes ont été proposées. Ces méthodes offrent la possibilité de générer des scénarios en considérant les critères de compatibilité et de

performance, soit séquentiellement (analyse morphologique), soit simultanément (QFD), soit de manière hybride (exploration de graphe). Pour les deux méthodes basées sur les matrices, un algorithme a été proposé pour faciliter l'identification de scénarios plausibles. Pour faciliter l'identification des scénarios plausibles et estimer leurs caractéristiques, un algorithme dédié a été construit pour répondre à ces questions. Cet outil n'était pas prévu initialement, mais lors de la phase de l'illustration, il est apparu utile d'automatiser le processus d'identification des scénarios plausibles et d'estimation de leurs caractéristiques (score de compatibilité global, score de performance global, etc.). En effet, cet outil a prouvé son utilité en permettant d'économiser à la fois du temps et des efforts. Quant à la méthode basée sur les graphes, une heuristique plus légère peut être appliquée en temps réel lors d'une réunion de décision.

Au chapitre 5, nous avons détaillé le troisième bloc du processus qui consiste à résoudre le problème. Plusieurs méthodes MCDA ont été répertoriées dans le bloc 3 pour évaluer et sélectionner un scénario recommandé : méthodes d'évaluation absolue, méthodes de comparaison relative par paire, et méthodes de comparaison relative à des points de référence.

Selon les acteurs industriels, un tel processus pourrait améliorer les mécanismes de coordination entre les décisions majeures de leurs projets. Même si les décisions sont interdépendantes, elles ne sont pas souvent considérées comme telles, et le processus que nous proposons permet (selon eux) d'avoir une meilleure vision des décisions à prendre ensemble et des conséquences des choix. Une étude de cas fictive, inspirée de projets réels passés, a été utilisée dans le chapitre 6 pour illustrer le processus de coordination multi-décision proposé. Nous avons appliqué la séquence méthodologique suivante : approche matricielle, simplification, approche descendante pour la définition du périmètre, structuration basée sur le QFD, sélection de scénarios basée sur le MR-sort.

Nous sommes convaincus que notre recherche fournira une base solide pour d'autres études portant sur la coordination de décisions multiples et interdépendantes dans le cadre de projets complexes, même si certaines perspectives académiques et industrielles doivent être abordées.

# Summary

<b>1</b>	<b>Chapter 1: Context and Industrial Problem.....</b>	<b>12</b>
<b>1.1</b>	<b>Introduction: the context of the Oil and Gas sector and of this Ph.D. ....</b>	<b>13</b>
<b>1.2</b>	<b>Characteristics of Oil and Gas Upstream Development Projects.....</b>	<b>14</b>
1.2.1	Main objectives .....	14
1.2.2	Main phases.....	15
1.2.3	Focus on phase #1: Appraisal and Conceptual .....	16
1.2.4	Focus on phase #2: Pre-project .....	18
1.2.5	Focus on phase #3: Development Phase .....	20
<b>1.3</b>	<b>Generic stakes of Oil and Gas development projects .....</b>	<b>21</b>
<b>1.4</b>	<b>Exploration of specific practical lacks in decision-making in Exploration &amp; Production Projects.....</b>	<b>22</b>
1.4.1	A 3-step approach to identify practical problems.....	22
1.4.2	Industrial Issue #1: a lack of formalization of interdependencies (implicit or vague knowledge) .....	25
1.4.3	Industrial Issue #2: a lack of information about possible impacts of decisions.....	28
1.4.4	Industrial issue #3: a need for coordination strategies.....	29
<b>1.5</b>	<b>Chapter conclusion: synthesis of industrial practical issues .....</b>	<b>33</b>
<b>2</b>	<b>Chapter 2: Research questions and proposals .....</b>	<b>34</b>
<b>2.1</b>	<b>Related work on projects.....</b>	<b>35</b>
2.1.1	Definition of project .....	35
2.1.2	Elements constituting a project .....	36
<b>2.2</b>	<b>Related work on project complexity and notably interdependencies.....</b>	<b>37</b>
2.2.1	Definition .....	37
2.2.2	Complexity frameworks.....	39
2.2.3	Focus on interdependencies in projects .....	43
<b>2.3</b>	<b>Decision-making in complex projects.....</b>	<b>47</b>
2.3.1	Managing a project is mostly making decisions.....	47
2.3.2	Generic issues associated with single decision-making .....	47
<b>2.4</b>	<b>Research gap #1: the need to formalize interdependencies between decisions.....</b>	<b>49</b>
<b>2.5</b>	<b>Research gap #2: the need for coordination between interdependent decisions .....</b>	<b>53</b>
<b>2.6</b>	<b>Research approach.....</b>	<b>55</b>
<b>2.7</b>	<b>Chapter conclusion: Research questions and proposal .....</b>	<b>57</b>
2.7.1	Research questions .....	57
2.7.2	Research Proposal: a 3-block process for formulating, structuring, and solving the multi-decision problem .....	58
<b>3</b>	<b>Chapter 3- Formulating the Problem: making <math>P</math> decisions considering <math>N</math> decisions (<math>1 \leq P \leq N</math>).....</b>	<b>59</b>
<b>3.1</b>	<b>Chapter introduction: the need for building first a global decision network to formulate a local multi-decision problem .....</b>	<b>60</b>
3.1.1	Our definition of interdependency between project decisions.....	60
3.1.2	The quantification of interdependencies between decisions.....	61
3.1.3	The usefulness of network modeling for interdependent decisions.....	62
<b>3.2</b>	<b>Modeling the global project M-decision network .....</b>	<b>63</b>
3.2.1	Graphs .....	63
3.2.2	Matrices.....	67
3.2.3	Intermediary conclusion about the methodological choice associated with decision network modeling.....	70
<b>3.3</b>	<b>Simplifying the M-decision network .....</b>	<b>73</b>

3.3.1	The reason why simplification could be useful in our context.....	73
3.3.2	Related work on network simplification .....	73
3.3.3	The two tests in other contexts .....	74
3.3.4	Intermediary conclusion about the possibility to apply network simplification in our context.....	75
<b>3.4</b>	<b>Formulating the local multi-decision problem (making <math>P</math> decisions among <math>N</math>).....</b>	<b>76</b>
3.4.1	Related work on clustering methodologies .....	76
3.4.2	The top-down approach.....	81
3.4.3	The bottom-up approach .....	84
3.4.4	Intermediary conclusion about the methodological choice associated with scope delimitation....	86
<b>3.5</b>	<b>Chapter conclusion: how to properly formulate the multi-decision problem .....</b>	<b>88</b>
<b>4</b>	<b><i>Chapter 4: Structuring the problem to propose relevant and plausible scenarios assembled from decisions alternatives .....</i></b>	<b>89</b>
<b>4.1</b>	<b>Introduction: the use of scenarios to add the notion of compatibility between decision alternatives.....</b>	<b>90</b>
<b>4.2</b>	<b>Building plausible then relevant scenarios (with a matrix-based approach).....</b>	<b>92</b>
4.2.1	Description of the morphological approach .....	92
4.2.2	Advantages and limitations, notably the lack of application in our context.....	94
<b>4.3</b>	<b>Building simultaneously plausible and relevant scenarios (with a matrix-based approach) .....</b>	<b>96</b>
4.3.1	Description of the QFD (Quality Function Deployment) approach .....	96
4.3.2	Applications of the QFD in our context .....	98
4.3.3	Advantages and limits .....	99
4.3.4	An example of an algorithm that can be applied for scenario generation .....	100
4.3.5	Intermediary synthesis about matrix-based approaches .....	103
<b>4.4</b>	<b>Building visual scenarios (with a graph-based approach).....</b>	<b>105</b>
4.4.1	The basic graph representing compatibility links between decision alternatives .....	105
4.4.2	Reshaping the graph to highlight good compatibility and remove bad compatibility .....	106
4.4.3	An example of heuristics that can be applied during a decision meeting .....	107
4.4.4	Extending the proposal by using the concept of stratified decisions .....	109
<b>4.5</b>	<b>Chapter conclusion: how to choose an appropriate scenarios generation approach?111</b>	
<b>5</b>	<b><i>Chapter 5: Solving the problem by selecting and recommending scenarios .....</i></b>	<b>112</b>
<b>5.1</b>	<b>Chapter introduction: the need for an adequate scenario selection and recommendation technique .....</b>	<b>113</b>
<b>5.2</b>	<b>Family #1: the absolute compensatory methods .....</b>	<b>114</b>
<b>5.3</b>	<b>Family #2: the relative pairwise comparison methods .....</b>	<b>115</b>
5.3.1	Analytic Hierarchy Process (AHP) .....	115
5.3.2	Analytic Network Processes (ANP) .....	117
<b>5.4</b>	<b>Family #3: the relative comparison to reference point methods.....</b>	<b>119</b>
5.4.1	The Pugh method .....	119
5.4.2	The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) .....	120
5.4.3	The ELimination and Choice Translating REality (ELECTRE) .....	122
5.4.4	The MR-Sort (Majority Rule Sorting) technique .....	124
<b>5.5</b>	<b>Chapter conclusion: how to choose an adequate scenario selection method? .....</b>	<b>126</b>
<b>6</b>	<b><i>Chapter 6: An illustrative example .....</i></b>	<b>129</b>
<b>6.1</b>	<b>Introducing the context and setting the methodological choices .....</b>	<b>130</b>
<b>6.2</b>	<b>Formulating the decision problem by selecting <math>P</math> decisions among <math>N</math>.....</b>	<b>131</b>
6.2.1	Modeling the global decision network .....	131
6.2.2	Simplifying or not the network?.....	132
6.2.3	Formulating the problem scope.....	133
<b>6.3</b>	<b>Structuring the problem and generating scenarios.....</b>	<b>134</b>

6.3.1	Building D-D and D-DA matrices for choosing the structuring approach .....	134
6.3.2	Building the DA-DA and PO-DA matrices for constructing the QFD.....	135
6.3.3	Proposing scenarios alternatives based on the QFD.....	137
<b>6.4</b>	<b>Evaluating and selecting among scenarios alternatives.....</b>	<b>140</b>
<b>7</b>	<b><i>Chapter 7: Conclusions and Perspectives</i> .....</b>	<b>143</b>
<b>7.1</b>	<b>Academic conclusions .....</b>	<b>144</b>
7.1.1	Wrap-up of the proposal and contributions .....	144
7.1.2	Focus on Research gap 1: the need to formalize interdependencies between decisions.....	147
7.1.3	Focus on research gap 2: the need for coordination between interdependent decisions.....	147
<b>7.2</b>	<b>Managerial implications.....</b>	<b>148</b>
<b>7.3</b>	<b>Limitations and perspectives.....</b>	<b>149</b>
7.3.1	Insufficient characterization of decisions alternatives.....	149
7.3.2	Defining the optimal moment when to make decisions.....	150
7.3.3	An assistance to build the methodological sequence.....	152
7.3.4	Two perspectives for practical implementation.....	152
	<b><i>Appendix 1: Questionnaire developed during the interview phase</i> .....</b>	<b>153</b>
	<b><i>Appendix 2: Extract from a description of the architects' activities, source (APP Hand BOOK)</i> .....</b>	<b>157</b>
	<b><i>Appendix 3: Conference paper presented in 2018 in the 21st edition of Lambda Mu Congress "Risk management and digital transformation: opportunities and threats"</i>.....</b>	<b>159</b>
	<b><i>Appendix 4: Conference paper Presented at the 21st International Dependency and structure modeling conference, DSM 2019</i>.....</b>	<b>160</b>
	<b><i>References</i>.....</b>	<b>161</b>

# Table of illustrations

Figure 1: Development process, from exploration to production.....	15
Figure 2: General Sequencing of a conceptual study, source APP HANDBOOK.....	17
Figure 3: General Sequencing of a pre-project study, source APP HANDBOOK .....	18
Figure 4: Sequential decision-making process .....	30
Figure 5: Partially parallel decision-making process .....	30
Figure 6: Sequential decision process, with the contracting strategy decided first .....	31
Figure 7: Sequential decision process, with the In-country Value decided first .....	31
Figure 8: Complex project elements, inspired by (Marle, 2002).....	36
Figure 9: Milestones of project complexity history, source (Bakhshi et al., 2016).....	39
Figure 10: Dimensions of managerial complexity in the MODeST model.....	42
Figure 11: Four types of interdependence, source, (Tsvetkova et al., 2019).....	45
Figure 12: Example of a work breakdown structure (WBS) for an oil and gas project, source (El-Reedy, 2016).....	49
Figure 13: Complete process consisting of 3 blocks .....	58
Figure 14: An example of a portion of a visual project map, source (Killen, 2007).....	62
Figure 15: The network of direct relationships between the project actors, source (Jaber 2016) .....	63
Figure 16: example of two types of contractor interdependence networks, source (Moussa & El-Dakhakhni, 2022).....	64
Figure 17: An example of Semantic network of delay causes, source (Zarei et al., 2018) .....	64
Figure 18: An extract of a decision making network, source (OMG, 2019) .....	66
Figure 19: Graphs of different types and their corresponding representation in adjacency matrix, source (Xu, 2020).....	67
Figure 20: FPSO Change Propagation DSM, source (Flanagan, 2007) .....	68
Figure 21: Example of Decision-Decision Matrix, source (Lederer et al., 2010) .....	69
Figure 22: Decision making environment DSM, source (Campagna et al., 2020).....	70
Figure 23: the Tramway (up) and CEA (down) networks, with complete (left) and simplified (right) versions.....	75
Figure 24: An example of flat clustering.....	77
Figure 25: An example of a dendrogram composed of 23 elements, source (Schaeffer, 2007).....	78
Figure 26: An example of Top-Down or divisive algorithms (M=10).....	79
Figure 27: An example of Bottom-up or agglomerative algorithms (M=10).....	80
Figure 28: Distribution of the decision dates within the cluster and identification of packages.....	83
Figure 29: General Case: a mix of synchronous and asynchronous strategies.....	83
Figure 30: Bottom-up identification of the environment of a single decision Di0 on a two-axis diagram .....	85
Figure 31: Identification of the (P-1) decisions to be made together with Di0 (Red-striped area) .....	86
Figure 32: A morphological space with 6 parameters, source (Im & Cho, 2013).....	93
Figure 33: The four phases of QFD, source (Bossert, 2021).....	96
Figure 34: Six parts of the house of quality, source (Bergquist & Abeysekera, 1996).....	97
Figure 35: Second QFD matrix “roof of the house”.....	98
Figure 36: Illustration of step 2 .....	101
Figure 37: A network of interdependent decisions (D-D), each with its own alternatives (D-DA) ...	105
Figure 38: Decision alternatives graph (DA-DA) .....	105
Figure 39: simplification of the interdependencies between alternatives by excluding red edges.....	106
Figure 40: pre-identification of coupling oriented relationships between pairs of alternatives .....	107
Figure 41: illustration of a generic stratified approach with all possible combinations.....	109
Figure 42: illustration of a reduced stratified approach, where paths at stratus N+1 depends on decisions at stratus N (and before) .....	110

Figure 43: Hierarchical structure of decision, source (Russo & Camanho, 2015).....	115
Figure 44: Pairwise comparison matrix of layer B to layer A, source (Russo & Camanho, 2015)....	116
Figure 45: Pairwise matrix of layer B to layer A, source (Russo & Camanho, 2015) .....	116
Figure 46: The relationship between AHP and ANP, source (Fei, 2020) .....	117
Figure 47: Graphic representation of the supermatrix generated in the ANP, source: (Saaty, 2008) .	118
Figure 48: Example of the Pugh matrix (Ullman, 2006).....	119
Figure 49: Graphical presentation of the TOPSIS method (Vavrek & Chovancová, 2020) .....	120
Figure 50: Global decision network .....	131
Figure 51: The simplified decision-decision graph and its adjacent matrix.....	132
Figure 52: making 5 decisions among 5.....	133
Figure 53: Decisions x Decisions DSM .....	134
Figure 54: Decisions x Decision Alternatives DMM. ....	135
Figure 55: Decision Alternatives x Decision Alternatives DSM .....	136
Figure 56: Project Objectives x Decision Alternatives DMM .....	137
Figure 57: Synthetic list of plausible scenarios .....	138
Figure 58: Plausibility-relevance diagram.....	139
Figure 59: Recommended plausible scenarios .....	139
Figure 60: Sorting of scenario alternatives using the MR Sort model .....	141
Figure 61: Retained scenarios .....	142

# List of Tables

Table 1: Extract from a description of the architects’ activities, source (APP HANDBOOK)..... 26

Table 2: Definitions of project complexity dimensions , source (De Toni & Pessot, 2021)..... 38

Table 3: TOE framework consisting of 15 T-elements, 21 O-elements and 14 E-elements, source (Bosch-Rekvelde et al., 2010) ..... 41

Table 4: Configurations that describe the interaction between the elements of the system/project, source (Yassine, 2004a) ..... 44

Table 5: the 5 families of research approaches by Mäkinen (1999)..... 55

Table 6: Notation and definition of the components modeled in the graph, source (OMG, 2019)..... 65

Table 7: Notation and definition of the links modeled in the graph, source (OMG 2019)..... 66

Table 8: Strengths and weaknesses of the two modeling methods studied ..... 71

Table 9: Strengths and weaknesses of the two structuring methods studied..... 104

Table 10: Strengths and weaknesses of the proposed solving methods ..... 126

Table 11: List of decisions ..... 130

Table 12: The chosen alternatives for each scenario..... 140

## 1 Chapter 1: Context and Industrial Problem

This Chapter introduces first the context of this Ph.D., notably the context of the Oil and Gas sector. Thus, it presents the generic stakes of complex development projects in this sector. Finally, it details specific issues and lacks in how decisions are made in such projects.

## 1.1 Introduction: the context of the Oil and Gas sector and of this Ph.D.

The Oil and Gas industry needs to deal with extremely dynamic market conditions (evolution of the cost per barrel, geopolitical situation, worldwide supply chains, business, environment, ...). Petroleum Exploration and Production (E&P) product prices have been subject to volatility in recent years and face severe constraints to maintaining minimum cost structures (Korloo, 2007).

The Oil and Gas industry is divided into three distinct sectors: the upstream, midstream, and downstream. Our context is the Upstream branch, which is considered as the most capital-intensive and important of the three oil and gas sectors (Shafiee et al., 2019). Upstream projects can be Offshore or Onshore.

The French Oil and Gas company TOTAL (now TOTAL Energies) had launched in 2013 a Chair with the Ecole Centrale Paris (now CentraleSupélec) on the topic of “managing risks related to contracts in development projects”. Two departments were initially involved in the supervision of the Chair and associated research projects: the “Projects and Construction” and the “Contract & Procurement” departments. Three Ph.Ds. and several smaller projects (Master’s internships, Master’s academic projects) have been carried out during this initial 5-year period. The main topics were related to several aspects of the management of such projects, respectively:

- the risks: analysis and decisions about how to mitigate them,
- the contractual strategy: decisions about how to break the project down into contracts, how to decide about the contract type, and how to select the contractor,
- the in-country value: how to decide a set of actions, within the project or outside the project, to bring long-term value to the country, even after the end of the development project.

At the end of this initial period of the Chair, the conclusion was that it had been useful to analyze separately different types of decisions, albeit the main perspective would be to provide a more integrated framework for mixing different types of decisions into a single model and decision-aiding process.

The Chair has been renewed in 2018 for another 3-year period and ended in December 2021. It consisted mostly of this Ph.D. at a more global and generic level, since the key object was the decision, either about technical or organizational elements. Moreover, this Ph.D. was initially supervised by 3 departments instead of 2 in the first period of the Chair. Unfortunately, the supervision has ended with the administrative end of the Chair at Fall 2021.

It is thus necessary to explain first the context of development projects under which this Ph.D. started to understand the initial questions and our proposals.

## 1.2 Characteristics of Oil and Gas Upstream Development Projects

The oil and gas projects are, as any megaproject, “large-scale, complex ventures that typically cost [USD one] billion or more, take many years to develop and build” (Iftikhar et al., 2022). They involve different countries, multinational companies, political and environmental organizations, etc. This section briefly presents their main objectives and details their phases.

### 1.2.1 Main objectives

In general, project objectives often tend to be limited to cost, time and quality/performance (De Wit, 1988). However, for upstream development projects, other objectives are considered, namely production, H3SEQ (health, safety, security, society, environment, and quality), and company image. Ensuring that projects are completed by the time the project was planned and according to budget costs are a key objective in the upstream development projects, as it is in all construction sectors. Indeed, delays and disruptions in these types of projects can have a significant impact on their success (Mohammed & Suliman, 2019). This is not surprising, since the penalty of a 1 day-delay in delivering a project means that production is delayed, which can be costing millions of euros per day (Ventroux, 2015). This underlines the importance of respecting the defined schedule and productivity objectives.

Adherence to H3SEQ objectives is essential for oil and gas companies. The prevention of chemical, biological, and psychosocial risks is an example of the health objective. Consideration of the impact of operations on civil society and local populations is an example of the societal objective. Ensuring safety in the operation of facilities and the process is an example of the safety objective.

Achieving these objectives creates value and contributes to the achievement of excellence in terms of image and links with stakeholders. The H3SEQ objectives also influence the economic performance of the company and its results. In Total Energies, several H3SEQ policy standards, including laws, rules, and processes, are defined at the preliminary project stage for application during project operations. Among the indicators that are used to calculate the performance of H3SEQ objectives we find the TRIR, which is an accident frequency rate, measured per million hours worked, and the HiPo, which is the number of reported events that could have had major or catastrophic consequences.

The public image of the company is very important in such projects, since the oil and gas development sector attracts increasing public attention and pressure. Every company seeks to improve its image by improving for example the efficiency of its operations. However, these measures are not only beneficial to the environment and the company's image, they are also financially beneficial and allow companies to comply with current and possibly future regulations (Schweitzer, 2010).

### 1.2.2 Main phases

These projects are divided into multiple phases that require considerable effort in terms of communication and careful coordination for their success (Lopes & de Almeida, 2013; Niayeshnia et al., 2020). Finding a location with hydrocarbon reserves is not enough to begin field development and production. It requires several years of careful planning and development before production can be initiated.

Thus, to ensure that the outcome meets company's objectives, oil and gas upstream development projects are planned and executed through a staged capital development process including several distinct phases. These phases involve multiple checking, preparation, and validation gates (see Figure 1 **Erreur ! Source du renvoi introuvable.**):

- Appraisal-Conceptual phase,
- Pre-project phase,
- Development project phase which comprises basic and detailed engineering, fabrication and construction, and commissioning.

These phases enable the management of project schedule with distinct deliverables for each of them. **In this research, the focus is on the phases preceding the Final Investment Decision known as FID.** During these phases, multidisciplinary project teams are organized to successfully complete each phase and make multiple decisions before reaching the final decision. However, these decisions influence each other, making the decision-making process potentially more complex. Moreover, these pre-FID decisions may and will have consequences on post-FID activities and decisions. For instance, an initial conceptual decision may put a constraint, or at least reducing the degrees of freedom for future fabrication phase, and the associated contractor award decision.

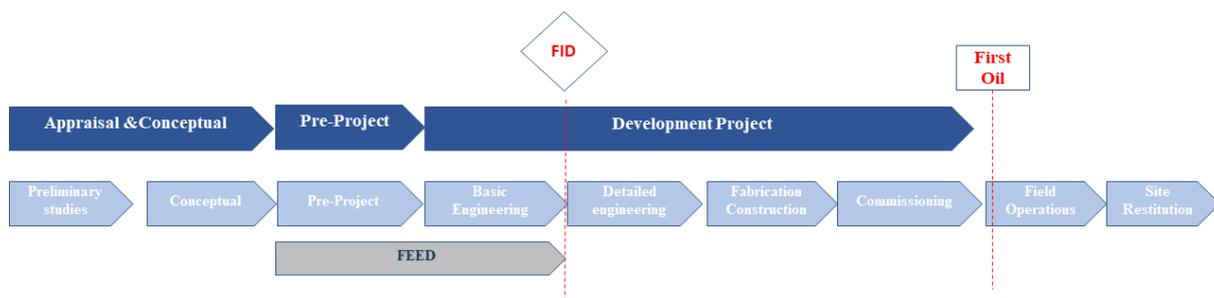


Figure 1: Development process, from exploration to production

We are now going to give information about the pre-FID phases, respectively Appraisal and Conceptual (grouping Preliminary studies and conceptual phases), Pre-project, and Basic Engineering.

### 1.2.3 Focus on phase #1: Appraisal and Conceptual

The main objective of this phase is to select an optimal development scheme after optimization of the pre-selected schemes to exploit a hydrocarbon discovery. The list of development schemes is generated in the screening step of the conceptual study. It is obtained by exploiting data acquired during the appraisal program, conducting a review and a comparative study of the possible development schemes. Once a development scheme is selected, the necessary facilities must be defined in terms of development architecture (e.g., number of wells and production), cost, schedule, production, and injection profiles. This development scheme will serve as a basis for the next development phase.

Thus, multiple conceptual decisions must be taken in this phase. These decisions require finalizing the definition and evaluation of subsurface objectives related to the reserves and selecting the recovery mechanisms to be implemented. It also requires quantifying sub-surface and project uncertainties and reduce them through an appropriate appraisal program (wells, tests, seismic, etc.) and studies.

#### 1.2.3.1 Deliverables

Different deliverables are produced during this phase, the main ones being:

- **Delineation Appraisal Strategy Report (DASR):** multidisciplinary technical document that contains the description of the appraisal strategy to be carried out to define the subsurface development perimeter, to improve the knowledge of the reservoir and to reduce the uncertainty.
- **The COMAD report at the end of the Preliminary phase:** it includes recommendations for appraisal activities and a summary of preliminary studies.
- **The Preliminary Study Report (PSR):** preliminary petroleum architecture studies and assessment recommendations available at the time of publication.
- **The COMAD report at the end of the Conceptual phase:** it mainly includes a synthesis of the conceptual study, recommendations for the choice of development scheme as well as information related to reserves, production facilities, planning of their implementation and cost estimates.
- **The Conceptual Study Report (CSR):** it presents the recommended development scheme and others information related to the reserve.

#### 1.2.3.2 Validation steps

Following a positive evaluation of a hydrocarbon discovery, conceptual studies are launched with a study kick-off meeting (KOM) and then decomposed into five steps as illustrated in Figure 2.

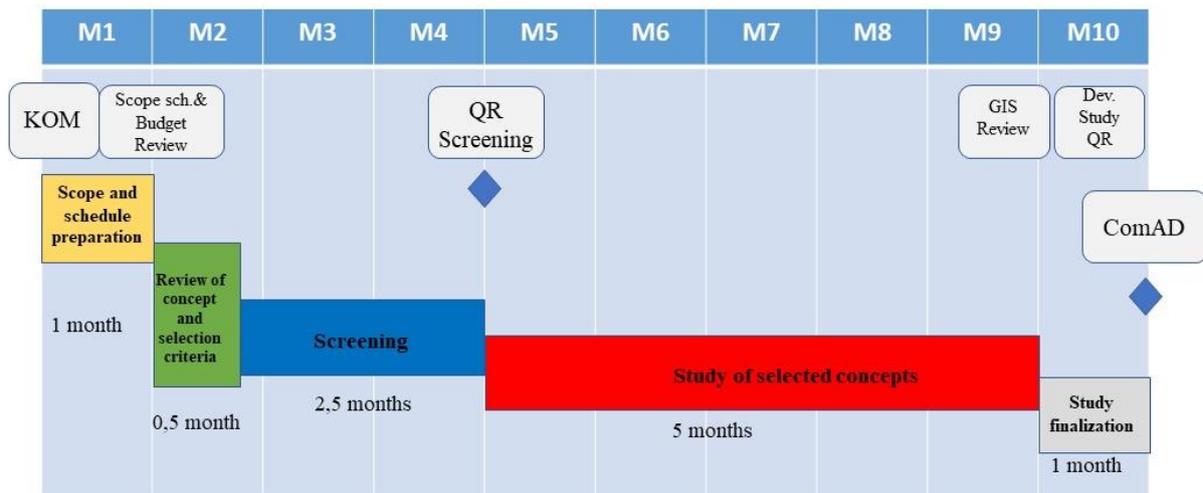


Figure 2: General Sequencing of a conceptual study, source APP HANDBOOK

More details about each study and validation step are provided in the following:

- **Preparation of the scope, schedule, and budget of the study:** during this study, an initial list of concepts is developed with relevant disciplines, including architects (APP), geoscientists (GIS), drilling entities (FP), ECP and ICS. At this stage, a consolidated timeline is also produced that outlines the relationships between each discipline's interventions, budget, key deliverables, and the actors who carry them out.
- **Scope Schedule & Budget Review:** the main objectives of this review include validating the information provided in the previous study, clarifying the relationship between tasks and disciplines, and defining the dates for the main deliverables.
- **Review of concepts and selection criteria:** during this study, a summary description of the concepts to be studied, a qualitative comparison and a list of issues to be analyzed in the screening phase are prepared.
- **Screening:** during this study, each discipline must conduct a comparative evaluation of the identified concepts based on the comparison grid developed in the previous study.
- **QR Screening:** the main purpose of this quality review is to validate the concepts to be rejected from the list and the reasons involved and the retained concepts for the conceptual phase.
- **Study of selected concepts:** during this study, each discipline explores the selected concepts in more detail and then identifies their strengths and limitations.
- **GIS Review:** Among the objectives of this review are the validation of the project scope and challenges, as well as the reservoir management policy.
- **Study finalization:** during this study, the results of each discipline are combined to summarize the advantages and limitations of each concept. This will be used to comment on the selection of concepts in the pre-project phase.
- **Dev. Study QR:** the purpose of this review is to ensure the quality of the conceptual study, recommend a development concept, identify critical issues to be studied in the pre-project phase, and prepare recommendations for submission to ComAD.
- **ComAD:** The purpose of this committee is to approve the appraisal strategy, the choice of development concept and the associated technical choices. It aims also to validate the development strategy, costs, schedule of the selected concept and then validate the transition to the pre-project phase.

The delineation program is submitted to EXPLEO for budgetary approval. Then, the development appraisal program is submitted to the E&P budget validation process.

### 1.2.4 Focus on phase #2: Pre-project

The objective of this phase is to prepare the final decision to exploit or re-exploit a hydrocarbon deposit, to build petroleum or transportation facilities. This decision is taken at the end of the basic engineering phase. During this phase, the activities conducted aim to further develop the development scheme and bring it to a level of technical detail that guarantees feasibility, operability. They aim also to estimate the investment and operating costs, as well as the expected production, with sufficient accuracy to provide a reliable economic calculation.

#### 1.2.4.1 Deliverables

Different deliverables are produced during this phase, the main ones being:

- **Pre-Project-Report (PPR):** it includes all the elements necessary to carry out the basic engineering studies. It consists of reports on subsurface studies, wells (architecture and productivity), surface (processes, utilities, and architecture, etc.), operations, HSE, safety, sustainable development, and site restitution. The "Reservoir Management Plan" is an example of the subsurface studies, it describes the understanding of the reservoir, residual uncertainties and risks, hydrocarbon recovery strategy, etc.).
- **Statement Of Requirement (SOR):** it is a reference document which describes in detail, for all disciplines, all the fundamental elements required for the progress of the project.
- **COMAD Report at the end of the pre-project phase:** it includes recommendations for the development scheme and provides a synthesis of the pre-project development study. This synthesis includes additional information mainly about the evaluation of the reserves, resources associated with the development, production and injections profiles, description of the production facilities and the planning of their realization, the definition of the contractual strategy and the cost estimate.

#### 1.2.4.2 Validation steps

Once the concerned Committee validates the deliverables of the pre- project, the passage to the basic engineering phase is authorized. However, the final investment decision (FID), which corresponds to the final decision to launch the development project, is subject to the initiative of the project owner (the affiliate or DIG), the approval of the CDEP/Coval and, if necessary, the approval of the COMEX. In addition to the above committees, the process is marked by discipline-specific reviews. Pre-project studies are launched with a study kick-off meeting (KOM) and then decomposed into five steps as illustrated in Figure 3.

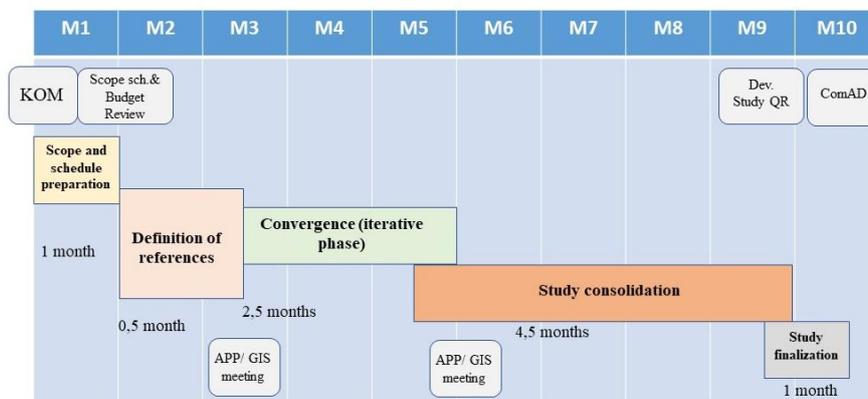


Figure 3: General Sequencing of a pre-project study, source APP HANDBOOK

More details about each study and validation step are provided in the following:

- **Preparation of the scope, schedule, and budget of the study:** this stage is also used to define the scope and content of the study for each discipline taking part in it and to produce a consolidated schedule of each discipline's operations. This schedule highlights the links between the disciplines, the budget, the key deliverables, and the actors carrying out each task. This stage ends with a Scope Schedule & Budget Review.
- **Definition of references:** this stage serves to prepare the work to be carried out by the disciplines concerned, finalize the bases of design (BoD), consolidate the results of specific studies or analysis such as laboratory studies on fluids (reference PVT), and define the scope of work of each discipline. At the end of this stage, a meeting is held by the APP and GIS entities to check progress made and make sure references are consistent.
- **Convergence (iterative phase):** the purpose of this iterative phase is for the GIS, FP, ECP and ICS disciplines to establish the reference production profiles integrating all the well constraints (number of wells and TLV), the subsea network layout and the results of flow assurance calculations in steady state. This stage is needed before each discipline can launch more detailed studies. It consists in exchanging intermediate versions leading to a consistent design of flow modeling from the reservoir to the export facilities. At the end of this stage, a meeting is held by the APP and GIS entities to check progress made and make sur the profiles derived from the integrated model are consistent.
- **Study consolidation:** the purpose of this study is for each discipline to fine-tune the definition and deliverables of the objects to be studied.
- **Study finalization:** this stage serves to validate and aggregate the results of each discipline's consolidation stages. It usually includes preparation and execution of the quality review and the follow-up of associated actions.

### 1.2.5 Focus on phase #3: Development Phase

The objective of this phase is to define and implement the petroleum facilities as designed in the pre-project phase, which require carrying out specific studies. The development project phase first combines the Basic Engineering, Detailed Engineering, Procurement of Equipment, Construction and Installation, Commissioning, Preparation of the Exploitation phase, Preparation and Execution of drilling, and Completion of Wells. Obviously, all this requires a good coordination between the external industrial actors including engineers, suppliers, constructors, installations, drilling company, etc.

#### 1.2.5.1 Deliverables

The deliverable of this phase is the petroleum installation (onshore, offshore, hybrid) which can be new (greenfield) or concerned with modifications and/or extensions of existing installations (brownfield or revamping). This installation must comply with DGEP rules, the requirements of the technical standards and of the local regulations, and the Statement of Requirements (SOR).

#### 1.2.5.2 Validation steps

Mandatory committees and reviews are planned in this phase. Four technical committees control the good progress of this phase as follows:

- Project Technical Committee (CTP n°1): it occurs at the beginning of the basic engineering and is held before the Project Validation Committee. Its purpose is to validate the organization for the conduct and supervision of the project and the contractual strategy.
- Project Technical Committee (CTP n°2): it examines at the end of basic engineering: deviations from the SOR, changes in the budget and schedule, progress, contract strategy, etc. It is followed by the Appraisal-Development Committee for project sanctioning in case this has not already been taken at the end of the pre-project process. This committee decides whether to go ahead with the project or not. This decision is the final investment decision (FID). This decision is extremely important in the oil and gas industry as it initiates project financing and execution. It is influenced by the estimated cost of the project. This estimate is important because in some cases, underestimation can result in financial difficulties for the company related to a significant overrun of the investment costs. Once this decision is made, the engineering, procurement, and construction (EPC) phase can begin, during which the project contractors procure the equipment and begin construction.
- Project technical committee (CTP n°3): it occurs during the construction. It examines, among other matters, the evolution of the budget and the schedule, and the progress of the project.
- Project technical committee of the project (CTP n°4): it occurs after the start of the production to ensure the return of experience.

Intermediate CTP can be organized depending on the complexity and duration of the project. In addition to the above committees, the process is marked by discipline-specific reviews. In case of exceeding the budget by more than 10%, a new approval by the CTEP/Coval and the COMEX is required.

### 1.3 Generic stakes of Oil and Gas development projects

There are many engineering issues to consider in E&P projects, starting with the probability of finding oil deposits at a given location. It is thus very important to estimate the amount of resources available there in order to judge the relevance of building an infrastructure adapted to the development of that field (Lopes & de Almeida, 2013).

The initial development phases preceding the FID are crucial as they condition the next steps. Thus, in the implementation phase, the project actors have limited influence on the project's outcome (Korloo, 2007). Therefore, to improve the performance of the project, it is essential to focus on the first phases of development, namely the conceptual phase, the pre-project phase, and the basic engineering phase. The result of a study conducted by Niayeshnia and co-authors showed that the engineering phase of EPC (Engineering-Procurement-Construction) projects is a critical factor to the effectiveness of a project and that careful execution of engineering activities can ensure its success (Niayeshnia et al., 2020). El-Reedy shared the same opinion, arguing that the success of the project as a whole depends on the engineering study performed in the front-end engineering (FEED) (El-Reedy, 2016).

For instance, according to Salama, to improve schedule performance, earlier phases, such as FEED, should be receiving more attention. Indeed, delays that occur during the pre-project engineering phase are a warning sign of very likely delays during the EPC phase (Salama et al., 2008).

To improve project performance and ensure that quality decisions are made, Korloo emphasized the importance of evaluating all possible alternatives in the early phases of development (Korloo, 2007). Yet, conducting a reliable FEED remains a very difficult task for most companies (Christodoulou, 2015). Coordination between the different entities of the project is essential in this phase (El-Reedy, 2016). A follow-up of the environmental and social impacts induced by the activities of the oil industry is demanded (Lopes & de Almeida, 2013).

## 1.4 Exploration of specific practical lacks in decision-making in Exploration & Production Projects

This section discusses the industrial problems identified from academic references and a field survey involving internal documents and a series of internal interviews. After the presentation of the approach, three practical issues are detailed.

### 1.4.1 A 3-step approach to identify practical problems

Some academic references have been first read to give elements to focus on during the second step, internal documents analysis. Then, a series of interviews has been carried out based on previous steps.

#### 1.4.1.1 *Academic literature review*

Although oil and gas projects development are important, they are not always completed as planned, failures are also possible (Elhoush & Kulatunga, 2017). They are often confronted with various problems that result, in certain circumstances, to the complete failure of the project (Niayeshnia et al., 2020). In accordance with these facts, Elhoush and Kulatunga (2017) cited a universal study of the performance of 365 oil and gas projects conducted by the auditing firms, Ernst & Young (EY) (EY, 2014). This study showed that a high percentage of projects failed to meet the approved time and budget (Elhoush & Kulatunga, 2017). In addition, according to the IPA (Independent Project Analysis) company, which is a research organization in the field of project analysis, there are real problems with cost overruns, and significant schedule delays in 78 percent of oil and gas projects (Merrow, 2012).

This particularly applies to upstream projects that fail for many reasons. Many indicators can be used to evaluate project performance, including cost, schedule, and production rates. However, cost performance is the key indicator to determine the success of such projects (Merrow, 2012; Rui et al., 2017). Following the same line of thought, according to Merrow (2012) - who is the founder of Independent Project Analysis (IPA) Inc-, a project is perceived as a failure when it deviates significantly from the promises established at the Final Investment Decision. This implies that the net present value (NPV) of the project was significantly lower than originally estimated, usually less than half (Merrow, 2012). The fluctuation in this value is usually due to projects experiencing significant cost overruns, significant delays in the delivery, unsatisfactory production rates, and the most economically destructive factor, the absence of production (Merrow, 2012).

According to Merrow, three main factors are responsible for the poor performance of upstream megaprojects. The first one is related to the completeness of the Front-End Loading (FEL), which presents the entire workflow preparing a project for the FID. Indeed, as the quality of the FEL degrades, the cost overruns increase rapidly. The second factor is related to the change in leadership positions, especially that of project director. The last factor is associated with the tight schedules set. Indeed, in recent study on EPC projects in the oil and energy sector, Niayeshnia and co-workers found that “most experts of this industry believe that careful execution of design and engineering activities is the key to project success” (Niayeshnia et al., 2020). This implies that the engineering phase of EPC projects plays a major role in the overall efficiency of the project.

Other causes of project failure have been cited by other authors in the oil and gas sector. One of the major causes cited in Elhoush and Kulatunga's study (2017) is inadequate and improper project risk management (Elhoush & Kulatunga, 2017). In addition, a study conducted by Ernst & Young (EY, 2014) distinguishes two types of factors that influence project performance, internal factors (business environment, project development, and project delivery) and external factors (regulatory and geopolitical challenges). These factors are compounded by economic instability, including oil price fluctuations, unpredictable weather and land conditions, procurement problems, design inadequacies, and slow decision making, all of which affecting projects. Other factors influencing projects include conflicts with government and local authorities, difficulties in obtaining permits, political and social pressure, and design error.

Decision-making in such projects is as Shafiee mentioned, inherently complex, requires extensive information gathering from multiple stakeholders, and is subject to uncertainties and risks (Shafiee et al., 2019). Decision-making is even more difficult when uncertainty is high, especially when operating in new locations, applying a new technology to a new region, or dealing with new business conditions. In addition, it requires the consideration of multiple factors such as technical, financial, environmental, societal, and geopolitical. Indeed, according to Korloo (2007), some major conceptual choices, such as the concept of a Deepwater field, are in many cases highly constrained by non-technical factors such as regulatory factors, host country preference, market conditions, local content requirements, and transfer of technology (Korloo, 2007). It is not surprising, therefore, that design shortcomings, inadequate design decisions and change in decisions are among the leading causes of delay in oil and gas projects (Niayeshnia et al., 2020; Zarei et al., 2018).

#### *1.4.1.2 Analysis of internal documents based on these references*

Since the beginning of my thesis, an analysis of internal working documents has been performed. They include Unidocs, Guides & Manuals (GM), Directives (DIR), Company Rules (CR), etc. This reading phase was mandatory to have a comprehensive and complete view of the decision-making mechanisms within TOTAL E&P from a documentary perspective.

This analysis lasted about 9 months and required almost twice as much time and effort as the initial academic reading phase and interview phase. This was due to three main factors. The first one is related to the large number of documents to review, approximately 150 documents. The second is related to the high level of detail of technical descriptions or project feedbacks that made it sometimes difficult to find what we were looking for. The third factor is that there were contradictions in these documents, about 20 contradictions. They required a lot of back and forth with my supervisors and, in some cases, with the appropriate manager / document owner to get specific explanations on certain points. At some point during this phase, this amount of information and the time pressure became overwhelming. This has led to a slow but sure convergence towards the different categories of questions that would be asked in the questionnaire.

#### *1.4.1.3 Questionnaire-based Interviews based on previous analysis*

To further my investigation, I then chose to use a qualitative research method. It consisted of a series of interviews with key actors from different disciplines involved in the decision-making process. A questionnaire was therefore developed, in a generic way, without specifying either the project phase or the entity to be interviewed. It is made up of 18 questions classified according to 6 categories that relate to how decisions are made in practice.

The categories are as follows:

- Category 1: general issues
- Category 2: how are the interactions between decisions managed (coordination of actors)?
- Category 3: how are the impacts that decisions might have in the future managed?
- Category 4: how is temporality managed in relation to a decision?
- Category 5: how is uncertainty managed in relation to a decision?
- Category 6: risks arising from decisions already made

More details about this questionnaire are included in Appendix 1.

For each participant, a first meeting is organized to present my research topic and the objectives of this questionnaire. Then the questionnaire is mailed to this participant. Once the questionnaire has been completed, a second meeting is organized to discuss each question in detail and thus avoid any ambiguity. The questionnaire was sent to a total of 12 participants, including Project Managers, Architecture Manager, Procurement and Equipment Manager, Global Category Manager, Facilities and Engineering Manager, etc. This phase lasted almost 4 months due to the difficulty of organizing close appointments and the delays in receiving responses to the questionnaire which varied from one to three weeks.

The aim of this questionnaire was to provide an overview of the existing decision-making processes within TOTAL, the process of managing multiple decisions, and finally the implementation of notions like decision temporality and uncertainty. More details about the structure of the questionnaire and the different questions posed are provided in Appendix 1.

This field survey allowed us to understand the main practical lacks in decision-making and to deduce three main industrial issues detailed hereafter, each one being supported by a dedicated literature review.

#### 1.4.2 Industrial Issue #1: a lack of formalization of interdependencies (implicit or vague knowledge)

In upstream development projects, many actors are involved in the design, development, and implementation activities. During these activities, multiple decisions must be made to ensure the smooth progress of the project. Some of them are collective and must be carried out collectively, while others are individual and require the involvement of only one actor. These decisions are generally interdependent as activities usually depend on each other. This is notably the case in the early phases of development (before the FID), where decisions are initially very conceptual and many interdependencies need to be identified and managed (Flanagan et al., 2008). In fact, these interdependencies add complexity to decision making, which must be managed with other considerations.

However, during the survey, we found that the modeling of interdependencies between decisions is partial and that there is a lack of awareness regarding interdependencies. This means that some interdependencies are already recognized and well managed, some are recognized but not necessarily considered in the decisions to be made, and others are not known. Unfortunately, the lack of consideration of some interdependencies occurs even though their long-term impacts are huge. It is also disappointing that insufficient efforts are made to identify these unknown and unfamiliar interdependencies. This situation is compounded by the fact that internal working documents lack an overall or partial mapping that could illustrate the possible interdependencies between decisions made by different entities. Such a mapping can help understand how each decision directly or indirectly influences the others and help identify the inputs needed for each decision.

We found that, in internal working documents, activities are emphasized more than decisions. A detailed sequence exists for the activities of each entity, including Architects (APP), TA, GIS, FP, PJC, Technical (TEC), Estimation (EST), HSE, etc... As shown in Table 1, which is an extract from the description of architect's activities, for each activity, the predecessors to be carried out before the launch of the activity in question and the successors to which this activity will contribute are mentioned. For more details, the complete description of these activities is included in Appendix 2. However, the format in which this information is presented does not reflect the reality of the situation. The complexity of the interdependencies between activities cannot be clearly visualized in textual documents.

It is important to mention here that there is a link between an activity to be performed and a decision to be made. In fact, some of the activities can lead to a decision, in the sense that a decision can be made based on the results of one or more activities. Therefore, the tables presented in Appendix 2 can be useful to understand the interdependencies between some decisions. Indeed, by studying the description of each activity to be carried out, their successors, as well as their predecessors, we can deduce some interdependencies between some activities and then deduct those between decisions. However, this deduction may not always be satisfactory, as confusions may arise between an activity to be performed and a decision to be made. Indeed, an activity does not always lead to a decision.

Table 1: Extract from a description of the architects' activities, source (APP HANDBOOK)

Civit name	Civit description	Main links between activities
<b>Scope, schedule, and budget preparation stage</b>		
Initial identification of concepts	The Architect identifies an initial list of concepts based on work carried out during the preliminary study.	Predecessor(s): - Dev.Study KOM. Successor(s): - Final list of concepts. - Final list of concepts and preparation of the scope, schedule, and budget (for each discipline). - Selection criteria: list of rejected concepts.
<b>Review of concepts and selection criteria stage</b>		
Brief technical description and identification of critical elements	The Architect prepares a technical description of the identified concepts with the help of the study managers from the GIS, FP, ECP, EXP and ICS disciplines. For each concept s/he identifies the critical elements that could affect the choice of concepts. These elements form a list of issues to be addressed in the screening stage.	Predecessor(s): - Scope Schedule & Budget Review. Successor(s): - Drafting of the qualitative comparison grid and list of issues to be analyzed.
<b>Screening phase</b>		
Consolidation and summary	The architect consolidates all the evaluations conducted by each discipline on the concepts selected in the previous stage. s/he summarizes this information by using the comparison grid to identify the concepts that will be analyze in greater detail during the study of selected concepts stage and justifies the concept rejections. The Architect prepares the QR Screening presentation material, which includes the list of assessed concepts, the differentiating criteria, and the justification for the rejections.	Predecessor(s): - Preliminary assessment of each concept (for GIS, ECP, ICS, EXP, PJC). - Specific studies of critical elements (for GIS, FP, ECP, ICS, EXP, LSO). - Preliminary CAPEX estimate (EST). - Preparation of benchmarks (EST). Successor(s): - QR Screening

 At this point, we conclude that there is a need to better understand, consider and manage the interdependencies of decisions.

This issue of interdependence between the different objects of a project has been addressed in the literature but with a variable ratio. In fact, this problem emerges since the product developed in EPC projects is unique and involves a variety of interconnected subsystems, requiring considerable effort of communication and interface (Yeo & Ning, 2002). Some authors have insisted on the fact that traditional project management methods used to manage interdependencies are less reliable in complex and modern projects. For instance, in the oil and gas industry, traditional project management techniques relying on discussion to identify and manage dependencies have been considered to be less effective at high complexity and limited experience (Flanagan, 2007). Indeed, projects in such industry are obliged to constantly operate in new territories where their experience and knowledge are limited. Therefore, more reliable methods were needed to identify and manage dependencies (Flanagan, 2007).

However, few studies have focused on the interdependencies that exist between decisions, even though they increase the complexity of decision-making process. Indeed, these interdependencies must be managed with other considerations. This is particularly the case in the early phases of development, as the work is initially conceptual and many interdependencies must be managed with other technical and non-technical aspects (Flanagan et al., 2008).

Knippenberg and his co-authors (2019) have stressed the importance of managing the dependencies between activities, actors, and deliverables but did not mention decisions (Knippenberg et al., 2019). Nevertheless, we cannot deny that managing these dependencies can help in understanding the dependencies between decisions. Indeed, ensuring good coordination of activities indirectly leads to good coordination of project actors, since these activities are allocated to actors. Further, ensuring good coordination of actors inevitably leads to good coordination of project decisions, since these actors are assigned to the decisions.

Formoso and co-authors have focused on managing interdependencies between decisions. According to them, given the multiple interdependencies that exist between decisions, it is not wise to make decisions sequentially (Formoso et al., 2002). This is since most decisions are influenced by other decisions made earlier and by others that will be made later in the project. It is therefore necessary to develop decision-making processes that are better adapted to context characterized by strong interconnection between its decisions and permanent interactions between its actors.

Some studies proposed methods to effectively manage interdependencies between decisions, we mention here the example of the dependency matrix. It is used to represent interdependencies to provide information and support decision making. More details about this and other methods are provided in the chapter 3.

The Society of Petroleum Engineers (SPE), in its technical guidance on decisions quality in upstream projects involving multiple companies, emphasized the importance of using a decision mapping tool to help managers visualize how decisions are sequenced and interrelated. Using this tool, several potential information can be captured (SPE Technical Report, 2015):

- Decisions that are influenced by previous decisions and must therefore be made after ensuring that these decisions have been finalized. This means that actors cannot make their decisions independently of each other and that they must interact, and exchange information.
- Decisions that are mutually dependent and must be made simultaneously
- Decisions that are independent and that can be made separately from other decisions.

In fact, according to the same reference, this mapping allows for faster and more appropriate decisions.

Despite the importance of properly managing the interdependencies between decisions, few studies have been conducted in the context of oil and gas projects. To our knowledge, none of them has proposed a comprehensive decision-making process that considers the interdependencies between decisions and possible scenarios in the project environment.

### 1.4.3 Industrial Issue #2: a lack of information about possible impacts of decisions

Decision-making also requires a clear understanding of the impacts of the decision being made on other decisions in its environment. Each decision made during the project has impacts that can positively or negatively affect other future decisions. However, during our survey, we noticed that there is a lack of information about possible impacts of decisions. It is important to mention here that this issue is linked to the first one. Indeed, understanding the different interdependencies between decisions is essential to anticipate their impacts. In other words, if we are not able to know to whom our decision is related, we cannot anticipate its impact except on direct short-term parameters.

Below is an example of a decision that, in some cases, is not sufficiently justified and the impacts are not properly considered. This example is about the validation of the development concept, which is linked to the data management strategy implemented during the development of the project.

According to industry practitioners, data acquisition in oil and gas exploration is becoming increasingly expensive and therefore limited data must be used appropriately to make wise and robust decisions. However, in some cases, it is necessary to accept to invest additional funds for acquiring more data, advancing the development concept, and improving the robustness of decisions.

Once a decision is made to not acquire certain data, it is important to be aware of the negative consequences this may have for the project. This decision can lead to the development of a concept that is not adapted to the studied context. Therefore, it is important to check the status of all necessary data acquisitions before sanctioning the project and to be aware of the impacts of any missing one.

Continuing in the same vein, in a policy of cost reduction, some decisions related to data acquisition can be postponed without careful consideration of their indirect impacts and without establishing a plan specifying when they will be made. This non-decision on the acquisition of this data can have a major impact on the progress of the project.

According to industrial practitioners, for some projects, there was a certain amount of information but not enough to be sure that the basis of the design was solid, which led to unpleasant surprises later. For the given example, it was necessary to understand the consequences of postponing a data acquisition, whether it was important to the final investment decision and project approval or not, and whether it was on the critical path or not. So, it is not about acquiring data or spending money immediately, but rather about reflecting, at the time of project approval, on the impact of not following a data acquisition plan.

 This leads us to emphasize the importance of gathering information about the possible impacts of decisions made before the project is approved and it becomes too late.

This issue of decision impacts has also been addressed in the literature. De Jesus and co-authors highlighted the importance of understanding these impacts, which are not always straightforward, as they can be obscure and non-intuitive (De Jesus et al., 2019). Furthermore, this understanding can be more complicated when the interdependencies between decisions are not properly identified.

The SPE technical report for upstream projects has mentioned that an important aspect to improve decision quality (DQ) is a full understanding of the impacts of each alternative being debated. This also includes considering how each alternative may affect other actors' choices and clearly communicating the trade-offs made between the possible alternatives. In addition, Mehrotra and Gopalan emphasized the importance of preventing negative impacts of strategic decisions made in the oil and gas industry in the UAE (Mehrotra & Gopalan, 2017).

While decision-makers can be often aware of the direct impacts of their decisions, it is doubtful whether this is the case for indirect impacts. This is especially true in a highly interconnected environment, where indirect impacts are likely to be difficult to anticipate without a solid understanding of possible interdependencies. Feng and Crawley attempted to improve understanding of these impacts by studying the indirect interactions that exist between actors in an oil and gas development project, as existing models only consider the direct relationships between the central organization and its stakeholders (Feng & Crawley, 2009). This, in turn, contribute to better decision making and anticipation of impacts. Indeed, once the relationships between stakeholders are clear, they can be more aware of the impact of their decisions on others.

#### 1.4.4 Industrial issue #3: a need for coordination strategies

During our survey, we have identified a need for coordination strategies adapted to the context of multiple decisions. This need can be perceived as a consequence of the initial issue previously highlighted. In fact, a lack of formalization of interdependencies implies poor coordination between actors and therefore their decisions. Without knowing how decisions are related to each other, it is difficult to coordinate them properly.

In the following, we cite some of the reasons that led us to identify this need. Indeed, in our investigation, we noticed that in Appraisal and Conceptual phase, architects select an optimal development scheme. This means that they limit the scope of possibilities for development scheme alternatives at an early stage of development. This lack of alternatives favors a rapid convergence in other conceptual and non-conceptual choices. Unfortunately, this rapid convergence has negative impacts on the decision-making process that may not be obvious to some. Thus, such convergence would suggest that the convergence was probably carried out without evaluating enough alternatives since there would be a lack of alternatives compatible with the chosen alternative, without considering the preferences of the other actors involved whose degree of freedom was greatly reduced, and thus without proper coordination in the decision making. In fact, to be aware of these problems, it is important to work together, to reflect on each other's decisions and to consider the impact of the choice to be made on the degree of freedom of the other actors involved.

In addition, we identified a lack of adaptation of the decision coordination strategy to the constraints that are different from one project to another. In the context of E&P development projects, there is a diversity of situations that change depending on the context of project. Based on discussions with industry stakeholders, it has been deduced that, in typical cases, the decision-making process is either sequential as shown in Figure 4 or partially parallel as shown in Figure 5.

In the first case, the development concept is decided first in the appraisal and conceptual phase, followed by the decision concerning the contractual strategy and the In-Country Value decision. In the second case, the concept is also decided first, but is followed by the in-country value decision and the contracting strategy, which are parallel.

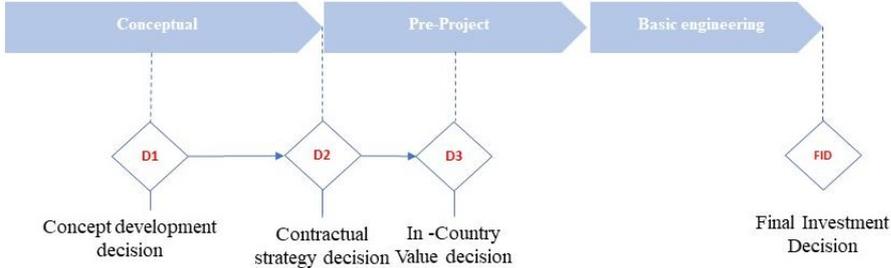


Figure 4: Sequential decision-making process

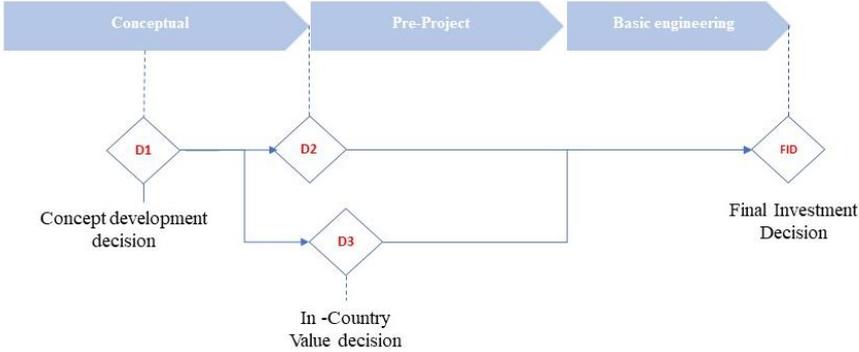


Figure 5: Partially parallel decision-making process

Discussions with industry stakeholders led us to conclude that these decisions are highly interdependent, require several iterations to be fully consistent and are not necessarily made in consideration of other decisions that affect them. Thus, a considerable effort of interface and communication is required to ensure the consistency of these decisions.

Indeed, the In-Country Value and the contractual strategies affect the choice of the development concept since they have a significant impact on it. For instance, for the contractual strategy decision, the list of bidders influences the conceptual choices made, the number of development concepts retained, and notably the chosen one. Therefore, before choosing a contracting strategy, it is essential to identify the possible alternatives and study their impacts on the development concept. It is indeed not appropriate to be in a situation where the only development concept chosen early is not adapted to the expertise of the available contactors and their skills.

Today, the contracting strategy is set at the end of the conceptual phase once the development concept is defined. Thus, this means that the spectrum of alternatives related to the concept is reduced early without considering the possible interdependencies between the different alternatives of contractual strategy.

This does not guarantee that the contracting strategy is constantly considered in the choice of the development concept.

Nevertheless, in other countries, the situation may be different given the conditions they impose on the project. In fact, some countries govern their tenders by deciding which contractors should be included in the list bidders. In this case, the decision related to the contractual strategy is made before selecting the concept, as shown in Figure 6.

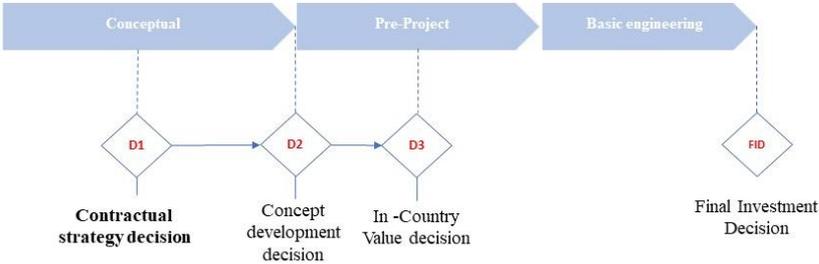


Figure 6: Sequential decision process, with the contracting strategy decided first

The same applies to the In-Country Value decision. Although it has an impact on the development concept decision, it is not always considered in the choice of that decision. It is important to mention at this stage that, in some cases, deciding on the development concept and then on the In-country Value strategy can generate negative impacts for the project. This is because some elements may not be considered in the design until the final development phase.

To better illustrate this idea, we take the following example of a project that was conducted in two countries. The plant was established in Angola and the pipelines passed through the Congo. The actors opted for a technically feasible development concept. However, they did not consider the local content requirements from the beginning, as these constraints were strong in Angola and insignificant in Congo. They assumed that the project was in Congo with Congo’s rules. Thus, the concept was no longer feasible and additional time was needed to negotiate host country rules. If they had considered the local content and contract strategy at the same time as the concept, things might have turned out differently. They might have realized earlier that the concept could not be applied in this context.

However, when security is complicated in a particular country or that the law imposes strong constraints related to local content, such as in Nigeria, the In-Country Value decision is considered from the beginning. Consequently, the choice of the development concept is decided after the In-Country Value decision, as shown in Figure 7.

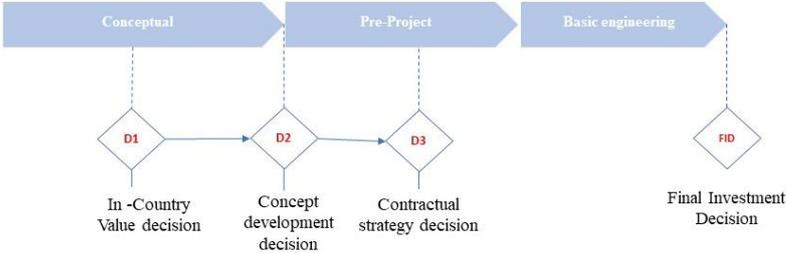


Figure 7: Sequential decision process, with the In-country Value decided first

What is disappointing here, for some actors, is that In-Country Value decision is not systematically enough considered in the decision-making process. In most cases, local content is considered as a constraint imposed by the law of the country in which they operate, whereas it could be turned into an opportunity.

In fact, considering local content early in the decision-making process can have positive effects on other futures projects. To further illustrate this idea, we take the following example, where we assume that the construction of a particular development concept requires a specific local industry that does not exist in the host country. We also assume that other projects will need and benefit from the same type of industry. It will therefore be interesting to invest in the development of this industry, as it will be useful for other projects. Moreover, in the business world, by developing an industrial fabric, it contributes to the improvement of the country, which will be appreciated by the government and will thus serve the image of the company.

This leads us to conclude that as soon as there is no constraint, the decisions are made sequentially with the development concept decided first.

With such decision-making processes, actors often tend to seek a development concept that is functional rather than the most economical possible. The most economical possible is achievable by integrating as much data as possible from the beginning and trying to have the most complete vision possible.

 Making decisions in that way is indeed feasible, which would explain the reason why actors don't attempt to do otherwise. However, with this decision-making process, decisions are not always adequately coordinated.

The issue of coordination between multiple decisions has also been addressed in the literature, given its potential benefits. In fact, more coordinated decisions allow for more timely and appropriate decisions (SPE Technical Report, 2015). Failure to coordinate decisions properly leads to blocking and slowing down decisions (Marle & Vidal, 2011a).

Managing interdependencies between these decisions is essential to ensure a better coordination between actors and therefore decisions. Once the interdependencies are clear, more coordinated decisions can be made. SPE mentioned how the type of interdependencies can help decision makers understand how their decisions are related to other ones and thus how to appropriately make decisions (SPE Technical Report, 2015). For instance, if decisions are mutually dependent, then they need to be made together. If decisions are independent of other decisions then they can be worked in parallel with others.

This suggests that as interdependencies between decisions increase, the need for effective synchronization, alignment, and adjustment between decisions increases. Indeed, the high degree of interdependence between the departments requires a high degree of coordination (Daft, 2010). In particular, oil and gas projects involve a variety of interdependent activities conducted by several disciplines and therefore a careful coordination is required for their successful completion (Niayeshnia et al., 2020). In accordance with the above, the success of a construction project, according to Bygballe and co-authors, requires the effective synchronization of the contributions of multiple project actors and interdependent activities (Bygballe et al., 2016). Additionally, an effective coordination is imperative to achieve an appropriate design in engineering and construction projects (Yeo & Ning, 2002).

In the literature, as already briefly mentioned, attention has also been paid to improving coordination between activities, deliverables, and actors. We can refer here to Bygballe and co-authors who stated that the existing literature has focused on the need for new methods and practices in the management of construction projects to allow for greater coordination between project actors (Bygballe et al., 2016). In fact, poor coordination between actors from different disciplines is identified as one of the causes of delays in oil and gas projects in Abu Dhabi (Salama et al., 2008). This is not surprising, as better coordination of actors is essential to ensure that the project is delivered on time and on budget (Knippenberg et al., 2019). In the study conducted by Barrick and co-authors, they confirmed that effective performance of interdependent groups of actors relies on good communication and close coordination (Barrick et al., 2007). Hui and co-authors stated that since activities in different phases of a complex project are interdependent from one phase to the next, poor coordination of these activities in the early phases of the project will spill over into later phases of the project. This leads to reduced performance in these phases (Hui et al., 2008).

It is important to mention here that ensuring good coordination between these elements including actors, activities, and deliverables implies also improved coordination between decisions.

## 1.5 Chapter conclusion: synthesis of industrial practical issues

In this chapter, the early phases of development prior to the Final Investment Decision, known as FID, are highlighted as being important to the success of the project. Based on the field survey conducted on the industrial context of the company TOTAL Energies, we have highlighted three main practical lacks in decision making process currently in place that emerge in the early phases of development.

Attributed to an insufficiently developed decision-making process adapted to complexity, managing the interdependencies between decisions, their possible impacts, and the coordination of multiple decisions remains a challenge. The importance of addressing these issues has been confirmed by industry stakeholders and the literature. Indeed, the success of complex oil and gas projects depends largely on these problems, which can lead to negative impacts in terms of performance and consistency of decisions made.

Addressing these industrial gaps, the objective of the Ph.D. work is to propose a decision-making methodology allowing a better identification and mapping of the interdependencies between decisions, a clearer understanding of the possible impacts of decisions, and a better coordination of the decisions to be made.

## 2 Chapter 2: Research questions and proposals

In this chapter, a state of the art based on the three industrial issues will be presented. It first includes a review of the literature on projects in general, then on the complexity of projects with a focus on interdependencies, and on decision making. Research gaps are then presented to raise research questions. Finally, research proposals are outlined.

## 2.1 Related work on projects

In this section, related work on projects in general is provided, including the definition of a project and its elements.

### 2.1.1 Definition of project

To define a project, many definitions are available in some academic or industrial project management standards. Some examples of each of them are given here. According to the Standard X50-105 of the French Association of Standardization (AFNOR, 2004), a project is a specific approach which allows to structure methodically and progressively a coming reality. A project is implemented to develop a response to the needs of a user, a client, or a customer. It implies an objective, actions to be undertaken with defined resources within a given timeframe. Based on the French association of engineers and technicians of estimation and planning, “a project is a unique process that consists of a set of coordinated and controlled activities with start and end dates undertaken to achieve an objective conforming to specific requirements, including the constraints of time, costs and resources” (AFITEP, 2010). Based on the Project Management Institute, “a project is a temporary endeavor undertaken to create a unique product, service or result” (PMI, 2013).

Two fundamental characteristics of a project are included in these definitions, namely its uniqueness and its time limit. Temporary means that every project has a definite beginning and end. Thus, temporary does not necessarily mean short-term. Some projects, such as those in the oil and gas industry, last for several years, but they all have an expected end depending on the achievement of project objectives. However, if the project objectives cannot be achieved, the project is abandoned.

Each project is unique means because any attempt to recreate the same project will always show differences from the original project. These differences may be related to one of the following parameters which are multiple and multidimensional (Marle, 2002): project location, financial aspects (budget, benefits, remuneration, etc.), time (start date, end date, etc.), quality (acceptability criteria, control methods, etc.), objectives, human resources (stakeholders, team composition, etc.), suppliers, and contractors. Indeed, these are the main characteristics that distinguish the activities or operations of a project from a project itself. In fact, usual activities tend to be repetitive functional activities and endowed with a low degree of uncertainty, while projects are by nature unique and temporary, with a high degree of uncertainty.

As is clear from these definitions, the definition of a project can be interpreted in different ways. In this thesis, we distinguish between the different types of projects. We will use the following definitions for simple and complicated projects as proposed by Bakhshi and his co-authors (Bakhshi et al., 2016). This choice is motivated by the fact that they were the only ones to consider interdependencies in their definition.

## Definitions

Simple projects can be defined as temporary activities undertaken to create products or services with clear cause-effect relationships (Bakhshi et al., 2016).

Complicated projects can be defined as temporary activities undertaken to create products or services with disputed cause-effect relationships (Bakhshi et al., 2016).

A project must achieve objectives, it needs to be developed through a well-defined process consisting of a set of phases. It has a life cycle from its launch to its end, which is reflected in the closing of contracts. The life cycle of a project contains several phases. Any project is subject to risks and requires decisions to be made in an uncertain and rapidly evolving context. It is exposed to pressure from shareholders, markets, and competitors, which leads to increasing constraints on cost, time, and quality parameters. It requires a lot of communication and coordination between the different stakeholders, as it is multi-resource and increasingly multi-company and multi-site.

### 2.1.2 Elements constituting a project

Several types of objects exist within a project, organized in hierarchical structures or graphs. Figure 8 outlines several elements, derived from the literature and definitions previously presented.

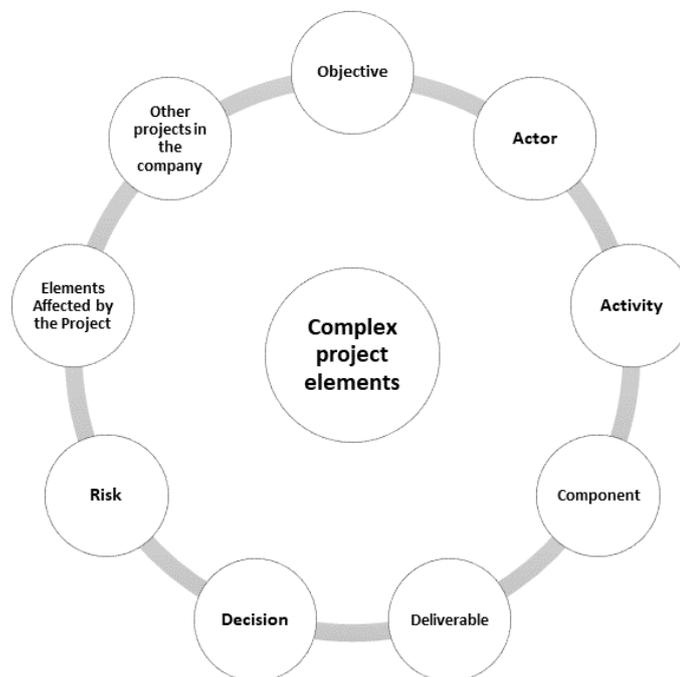


Figure 8: Complex project elements, inspired by (Marle, 2002).

These elements are described in the following list:

- **Objective:** “An end towards which efforts are directed. Expected result. Criterion for measuring performance.” (Ward, 1997)
- **Actor:** “a person, a group or an institution, that may be affected or may affect the planned actions of the project”(Bjugn & Casati, 2012).
- **Activity:** It consists of a set of activities performed by resources, over a certain period of time, and producing a concrete, material result or deliverable (Marle, 2002).
- **Component:** Standard element used in the construction of industrial products.
- **Deliverable:** It is an intermediate or final result produced as a result of an activity or set of activities. It is a tangible object intended for distribution to a user. A statement of requirements, feasibility study, report, software, or application are all examples of deliverables.
- **Decision:** A choice made by one or more actors on a potential alternative among others evaluated.
- **Risk:** A risk is an uncertain event that, if it occurs, may negatively or positively affect the project objectives.
- **Elements affected by the project:** they are consisting of elements of different natures such as activities, deliverables, actors, decisions that can be affected by the progress of the project.
- **Other projects in the company:** Temporary activities undertaken to create products or services with a clear or disputed causal link, depending on the case (Bakhshi et al., 2016).

## 2.2 Related work on project complexity and notably interdependencies

In this section, related work on project complexity is provided, including the definition of complexity, complexity frameworks, and a focus on interdependencies in projects.

### 2.2.1 Definition

We are living in a world surrounded by complexity, starting with ourselves to find out that we are perhaps the most complex system in the universe. As our world progresses rapidly, the pressure to build more complex systems is increasing, starting with vehicles, airplanes, and civil construction and engineering projects. This has contributed to the development of numerous research on this subject. Indeed, interesting complexity concepts and definitions have been produced since then, making the popularity of complexity concepts increasing (Sage et al., 2011). This has led to different definitions and complexity frameworks. We will start with the definitions and then discuss further the frameworks of complexity.

To define complex in its general sense, Maylor and his co-authors cited the definition proposed by Random house Webster's College Dictionary which states that complex means “composed of many interconnecting parts” (Maylor et al., 2008).

As described by Marle, a project is a complex system in a complex environment (Marle, 2002). Several authors have shared the same vision, including Javad Bakhshi and his co-authors who argued that, “this is evident in the basic definition of complexity, which is defined as an entity consisting of many varied interrelated parts and elements such as tasks, components, and interdependence” (Bakhshi et al., 2016). Complexity has become one of the most important and

discussed issues in the field of project management, resulting in different definitions of project complexity in the literature.

Baccarini is considered one of first researchers to propose a definition of project complexity (Fitsilis & Damasiotis, 2015; Hossny et al., 2021). He considered complexity as something "composed of many varied and interdependent parts" which can be expressed in terms of "differentiation", the number of varied parts, and "interdependence", the degree of interrelation between these parts (Baccarini, 1996; Fitsilis & Damasiotis, 2015). This leads us to conclude that every project contains a certain degree of complexity, since every project in the world contains parts such as activities, components, and interdependence.

Chapman (2016) cited Turner and Cochrane's (1993) definition of a complex project as one that " exhibits a high degree of uncertainty and unpredictability, emanating from both the project itself and its context." Such a definition suggests that complexity does not result from experienced and controlled situations, but rather from situations that are unpredictable.

According to the Geraldi and his co-authors (2011), project complexity is defined by its framework composed of 5 elements structural complexity, uncertainty, dynamics, pace, and socio-political complexity (Geraldi et al., 2011). Based on the research work of Sheard and Adviser- Mostashari, "complexity is the inability to predict the behavior of a system due to large numbers of constituent parts within the system and dense relationships among them" (Mostashari & Sheard, 2012). From this perspective, we can deduce that any complex project is conducted in an unpredictable and constantly changing technological, political, cultural, and socio-economic environment, potentially involving hundreds, or even thousands, of interrelations (Chapman, 2016).

From these definitions, we can identify four major dimensions of complexity: diversity, interdependence, dynamicity, and uncertainty. These dimensions were confirmed according to key contributions from the general project management literature (De Toni & Pessot, 2021). The following Table 2 provides definitions of these complexity dimensions.

*Table 2: Definitions of project complexity dimensions , source (De Toni & Pessot, 2021)*

<b>Dimensions</b>	<b>Definition</b>
<b>Diversity</b>	Size, number, heterogeneity and variety of the elements and subunits of the project, including hierarchies.
<b>Interdependence</b>	Degree and emergence of interactions and connections among the elements and subunits of the project.
<b>Dynamicity</b>	Flux, rate of delivery and dynamic changing of the project; it includes the temporal aspects (speed).
<b>Uncertainty</b>	Linked to the unknowns, variables to predict and interpret, manageability and planning of the project in terms of novelty, experience, and availability of information.

As we have seen, the definition of complexity has been articulated by several authors and perceived in different ways, as there is no consensual definition of what it is in the literature (Azim et al., 2010; Fitsilis & Damasiotis, 2015; Hossny et al., 2021; Ochieng et al., 2013; Vidal, 2009; Xia & Chan, 2012). This is not necessarily a bad criticism, as our perception of

complexity and the different approaches to deal with it should not remain the same, but be continuously reviewed and progressively improved (Chapman, 2016).

This thesis considers the definition of project complexity proposed by Vidal as it was the only definition found that integrates factors of complexity (Vidal, 2009).

**Definition**  
 Project complexity is the property of a project which makes it difficult to understand, foresee and keep under control its overall behavior, even when given reasonably complete information about the project system. Its drivers are factors related to project size, project variety, project interdependence and project context (Vidal, 2009).

For the definition of a complex project, the literature lacks a clear one. More focus has been placed on the definition of project complexity. In this Ph.D. thesis, a complex project is defined by the following simple definition.

**Definition**  
 A complex project is a project that has a number of characteristics related to complexity and to a certain degree.

2.2.2 Complexity frameworks

As for complexity frameworks, they have been developed to formalize the emergent and unpredictable nature of projects, which has led to different complexity frameworks. To bring more clarity to complexity frameworks, their evolution is detailed in an extensive systematic literature review as shown in Figure 9. Its objective is to define complexity in the context of project management (Bakhshi et al., 2016).

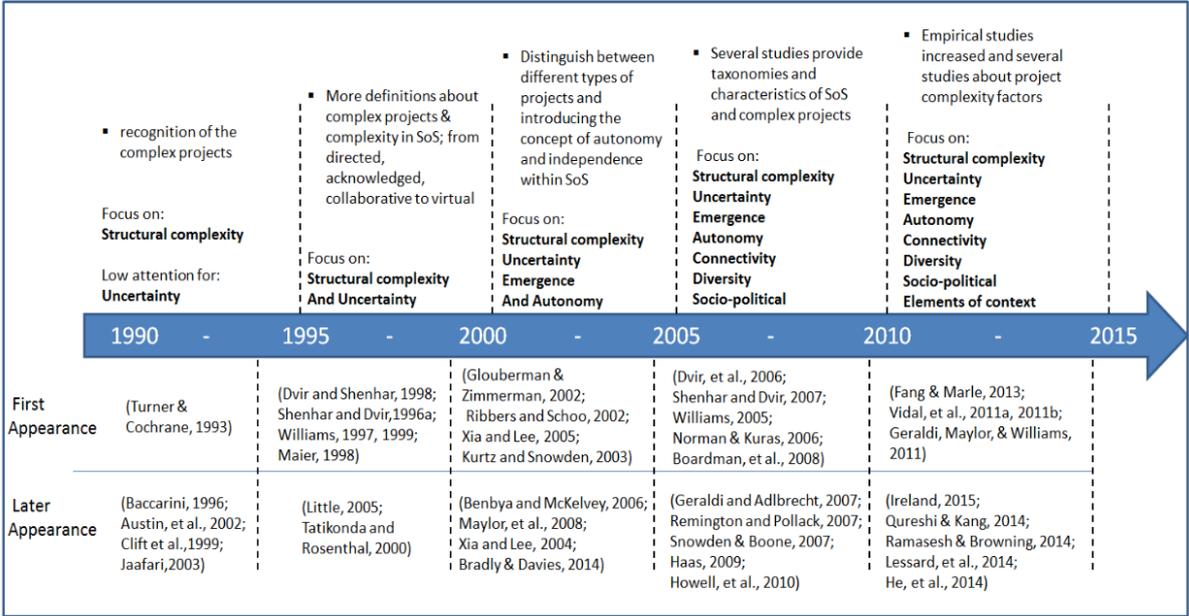


Figure 9: Milestones of project complexity history, source (Bakhshi et al., 2016)

To summarize, different sources of project complexity can be highlighted based on the information mentioned above. For instance, the frequency of changes during a project and the number of elements impacted by these changes, adds complexity to the project.

There is also the complexity of the product to be developed, the pressure of the market and competitors, technical uncertainties, the number of decisions to be made and risks. For oil and gas projects, the geographic location of stakeholders can be also a source of complexity. Indeed, project coordination becomes more difficult when stakeholders are geographically distant from each other (Vidal, 2009).

Another source of complexity to mention in such projects, is the number of actors and stakeholders to be coordinated during the project life cycle. Thus, this can lead to another source of complexity that is related to the number of interfaces in the project organization. As the number of actors increases, so does the number of decisions, making it more difficult to coordinate these decisions and predict their impact. This is likely to be more complex when considering the interdependencies that may exist between these decisions, given that the diversity of relationships and interactions between the project elements is also an important source of complexity (Vidal et al., 2011).

In accordance with the above, according to Vidal, four groups of factors are related to project complexity. The first is related to the size of the project, the second to project variety, the third to project interdependence which is defined as the existence of relationships between project elements and the fourth to project context (Vidal, 2009).

In an effort to better manage project complexity, Bosch-Rekvelde and co-authors have developed a detailed framework named TOE (Technical, Organizational, and Environmental) to analyze the complexity of large engineering projects (Bosch-Rekvelde et al., 2010). This framework includes 50 elements relevant to the complexity of the project, classified in the following three categories, as it was concluded that they affect the complexity in projects: technical complexity, organizational complexity, and environmental complexity. For simplicity, fourteen subcategories were identified within TEO so that elements could be easily assigned to each category. These subcategories are as follows (T: objectives, scope, tasks, experience, and risk; O: size, resources, project team, trust, and risk; E: stakeholders, location, market conditions, and risk).

The following Table 3: TOE framework consisting of 15 T-elements, 21 O-elements and 14 E-elements, source (Bosch-Rekvelde et al., 2010) illustrates an extract of this framework.

Table 3: TOE framework consisting of 15 T-elements, 21 O-elements and 14 E-elements, source (Bosch-Rekvelde et al., 2010)

TOE	Sub-ordering	ID	Source L/E/B <sup>1</sup>	Elements defined	Explanation
T	Goals	TG1	L	Number of goals	What is the number of strategic project goals?
T	Goals	TG2	B	Goal alignment	Are the project goals aligned?
T	Goals	TG3	B	Clarity of goals	Are the project goals clear amongst the project team?
T	Scope	TS1	B	Scope largeness	What is the largeness of the scope, e.g. the number of official deliverables involved in the project?
T	Scope	TS2	B	Uncertainties in scope	Are there uncertainties in the scope?
T	Scope	TS3	E	Quality requirements	Are there strict quality requirements regarding the project deliverables?
T	Tasks	TT1	B	Number of tasks	What is the number of tasks involved?
T	Tasks	TT2	B	Variety of tasks	Does the project have a variety of tasks (e.g. different types of tasks)?
T	Tasks	TT3	B	Dependencies between tasks	What is the number and nature of dependencies between the tasks?
T	Tasks	TT4	B	Uncertainty in methods	Are there uncertainties in the technical methods to be applied?
...					
O	Size	OS1	L	Project duration	What is the planned duration of the project?
O	Size	OS2	B	Compatibility of different project management methods and tools	Do you expect compatibility issues regarding project management methodology or project management tools?
O	Size	OS3	B	Size in CAPEX	What is the estimated CAPEX of the project?
O	Size	OS4	B	Size in Engineering hours	What is the (expected) amount of engineering hours in the project?
O	Size	OS5	B	Size of project team	How many persons are within the project team?
O	Size	OS6	E	Size of site area	What is the size of the site area in square meters?
O	Size	OS7	B	Number of locations	How many site locations are involved in the project, including contractor sites?
O	Resources	ORE1	B	B	Project drive Is there strong project drive (cost, quality, schedule)?
O	Resources	ORE2	B	Resource and skills availability	Are the resources (materials, personnel) and skills required in the project, available?
O	Resources	ORE3	B	Experience with parties involved	Do you have experience with the parties involved in the project (JV partner, contractor, supplier, etc.)?
O	Resources	ORE4	E	HSSE awareness	Are involved parties aware of health, safety, security and environment (HSSE) importance?
O	Resources	ORE5	B	Interfaces between different disciplines	Are there interfaces between different disciplines involved in the project (mechanical, electrical, chemical, civil, finance, legal, communication, accounting, etc.) that could lead to interface problems?
...					
E	Stakeholders	ES1	B	Number of stakeholders	What is the number of stakeholders (all parties (internal and external) around the table, pm=1, project team=1, NGOs, suppliers, contractors, governments)?
E	Stakeholders	ES2	B	Variety of stakeholders' perspectives	Do different stakeholders have different perspectives?
E	Stakeholders	ES3	B	Dependencies on other stakeholders	What is the number and nature of dependencies on other stakeholders?
E	Stakeholders	ES4	B	Political influence	Does the political situation influence the project?
E	Stakeholders	ES5	B	Company internal support	Is there internal support (management support) for the project?
E	Stakeholders	ES6	B	Required local content	What is the required local content?
E	Location	EL1	E	Interference with existing site	Do you expect interference with the current site or the current use of the (foreseen) project location?

Bosch-Rekvelde and co-authors (2010) cited the MODeST framework proposed by Maylor and his co-authors which provides a structural model based on managerial complexity. It includes five dimensions, as shown in Figure 10: mission, organization, delivery, stakeholders and team, which are then refined to present detailed concepts for each dimension (Maylor et al., 2008). They also mentioned interdependence within a project as a major factor of complexity. They noted that the complexity of interdependence exists at two levels in their model: between the dimensions themselves and between the concepts that make up the model.

Thus, the interdependence among the concepts was a frequent and repeated challenge for practitioners. There are commonalities between the TOE framework and the MODeST model. However, the advantage of the TOE framework over the MODeST model comes from the combination of both sources: the literature and emerging empirical research.

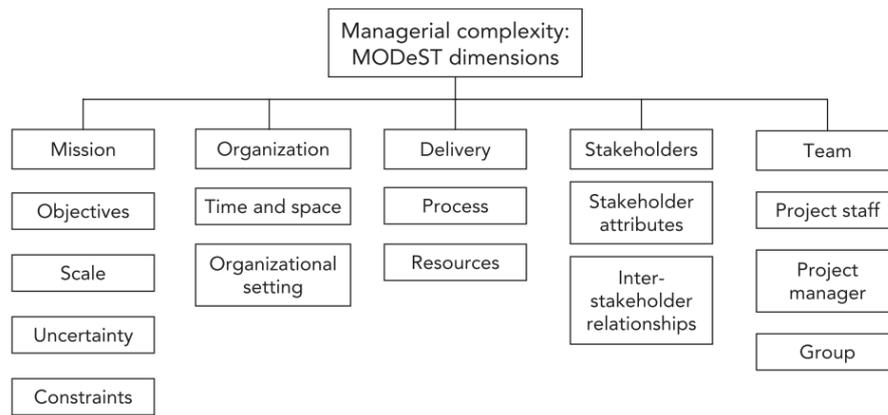


Figure 10: Dimensions of managerial complexity in the MODeST model

Chapman has developed a framework to examine the factors and characteristics of project complexity in the field of rail megaprojects (Chapman, 2016). Five elements compose the proposed framework, namely project governance, project initiation, complexity dimensions, assurance processes, and evolving project management maturity. According to Chapman, two essential characteristics are associated with this framework: first, it considers that the degree of complexity evolves throughout the project life cycle; second, it considers aspects of complexity that are both under the control of the project and those that arise from its environment. Other studies have focused on measuring project complexity. Among these studies, we mention the one conducted by Poveda-Bautista and his co-authors, in which they proposed a new tool to assess the complexity of Information Technology (IT) project management using a complexity index (Poveda-Bautista et al., 2018). This index is intended to measure, in each context, the effect of complexity factors in IT projects. The factors addressed in this assessment tool are derived from project management standards, specifically the International Project Management Association (IPMA) approach, and from literature specific to IT projects.

The focus in this Ph.D. work is on the management of project interdependencies, since interdependencies are potentially one of the main drivers of project complexity, as pointed out by several authors (De Toni & Pessot, 2021; Marle, 2002; Moussa & El-Dakhakhni, 2022; Rodrigues & Bowers, 1996; Vidal, 2009). In a project, there are a variety of interdependencies, between its elements, as well as between sites, divisions and companies involved in the project, between information systems, and more. Concerning the interdependencies between the project elements, those include the interactions between objectives, actors, deliverables, activities, risks, and decisions. The focus in this work is on decisions and their interdependencies since that decision making in complex projects can be challenging.

### 2.2.3 Focus on interdependencies in projects

Interdependence exists between all types of project objects. Different types of interdependencies are possible. Pimmler and Eppinger (1994) have proposed to classify the interactions of system elements into four categories: spatial, energetic, informational and material (Pimmler & Eppinger, 1994). Thompson (1967) argued that interdependence could be also based on activity interdependence (Tjosvold, 1986). Interdependence of activities refers to the extent to which the outputs of these different activities impact each other (Thompson, 1967). According to Barbini and Masino, Thompson classified interdependent relationships within an organizational structure into three types, on the basis of the intensity of interactions and behaviors required to perform a given activity: pooling, sequential and reciprocal (Barbini & Masino, 2017).

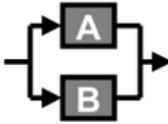
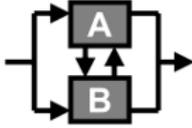
- **Pooled interdependence:** This type is the weakest form of interdependence. The two studied elements are independent of each other, and no exchange of information occurs between them. For this type of interdependence, minimal coordination is required between the responsible entities or actors.
- **Sequential interdependence:** The first element A must function properly so that the second element B can function properly, considering that the result of element A is the input to operation B. In this form of interdependence, an exchange of information is necessary for ensuring that each element functions properly.
- **Reciprocal interdependence:** This type is the highest form of interdependence. This means that the two studied elements exchange mutually materials and information. This situation occurs when the result of element A is the input to operation B, and conversely. Thus, it is important to note that decision-making, communication, and coordination issues are more important for this type of interdependency.

According to Yassine (2004), three main configurations describe the interaction between the elements of the system/project: parallel, sequential, and coupled (or interdependent). In the first configuration, there is no interaction between the system elements (project). In this case, element B is completely independent of element A and thus they can be executed be synchronously without the need for any information transfer. In the second configuration, corresponding to a sequential relationship, the two elements of the system (project) are dependent and therefore there is an interaction between the elements of the system (project). In other words, one of the elements influences in a unidirectional way the functioning of the other element.

For example, in terms of project decisions, decision A must be made before decision B because it must provide necessary information for decision B. For the last configuration, corresponding to coupled relationship, the interaction between the two elements is tightly linked: decision A influences B and decision B influences A. So, A can be executed only by considering B and the same applies to B.

As we can see, these three configurations have a lot in common with those proposed by Thompson (1967). However, Yassine (2004) has also proposed a graphical and matrix representation for these configurations, shown in Table 4.

Table 4: Configurations that describe the interaction between the elements of the system/project, source (Yassine, 2004a)

Relationship	Parallel	Sequential	Coupled																											
Graph representation																														
Matrix representation	<table border="1"> <tr><td></td><td>A</td><td>B</td></tr> <tr><td>A</td><td>■</td><td>■</td></tr> <tr><td>B</td><td>■</td><td>■</td></tr> </table>		A	B	A	■	■	B	■	■	<table border="1"> <tr><td></td><td>A</td><td>B</td></tr> <tr><td>A</td><td>■</td><td>■</td></tr> <tr><td>B</td><td>X</td><td>■</td></tr> </table>		A	B	A	■	■	B	X	■	<table border="1"> <tr><td></td><td>A</td><td>B</td></tr> <tr><td>A</td><td>■</td><td>X</td></tr> <tr><td>B</td><td>X</td><td>■</td></tr> </table>		A	B	A	■	X	B	X	■
	A	B																												
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B	X	■																												
	A	B																												
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B	X	■																												

Thompson (1967) also proposed several coordination strategies to resolve these forms of interdependence (standardization, planning and mutual adjustment respectively). Indeed, according to him, understanding the intensity of interdependencies between project elements, such as decisions, is pivotal to understanding how a decision-making process should be designed. For example, “complex tasks associated with mutual dependencies require structures that allow for mutual adjustment”. Daft shares the same opinion, arguing that “as interdependencies increase, mechanisms for coordination must also increase” (Daft, 2010).

Further, we believe that the same applies to decisions, since highly interdependent decisions require increased coordination needs. Therefore, we argue that a better understanding of interdependencies is essential to improve the coordination of multiple decisions. As cited in the Daft’s book, as interdependence increases, the risk of encountering problems between project members increases. This is since high interdependence leads to an increased effort of communication, coordination, and certainly of decision making (Daft, 2010).

Indeed, with a high level of interdependence, actors must spend time coordinating and sharing information. This also applies to the components of a given product. The way in which the components of a given product interact with each other defines the degree of coordination required between development teams (Pimmler & Eppinger, 1994). It is therefore important that our development methodology takes these interactions into account when making decisions in complex projects.

Tsvetkova and co-authors (2019) used the three types of interdependence proposed by Thompson previously presented, and broke down the third type, called reciprocal interdependence, into two types of interdependence: compatible-reciprocal and contentious-reciprocal interdependence (Tsvetkova et al., 2019). Further, for each new type of interdependence, they proposed the coordination mechanism that corresponds to it:

- **Compatible-reciprocal interdependence:** It requires mutual adjustment to achieve compatibility between the outcomes of the interdependent actors' activities. However, this alignment does not imply conflict between the respective goals of the actors involved. Hence, this type of interdependence can be managed simply by requiring that communication and confirmation occur frequently between the implicated actors.

- **Contentious-reciprocal interdependence:** It also requires mutual adjustment to achieve alignment between the outcomes of the interdependent actors' activities. However, achieving alignment now involves conflict between one or more of the respective sub-goals of each of the actors involved. This type of interdependence represents the most complex and expensive type of interdependence to coordinate.

Tsvetkova and co-authors (2019) also proposed a representation for each type of interdependence, illustrated in the Figure 11 below. Mutual interdependencies are modeled by single arrows, and sequential interdependencies by multiple arrows in sequence. Compatible mutual interdependencies have happy faces and a handshake symbolizing their compatible goals. Conflicting mutual interdependencies have angry faces and lightning bolts symbolizing their conflicting goals.



Figure 11: Four types of interdependence, source, (Tsvetkova et al., 2019)

Hui and co-authors have defined two types of activity interdependence in complex projects, the within-stage and the between-stage interdependence (Hui et al., 2008):

- **Within-stage interdependence:** It refers to related activities performed simultaneously during a particular project stage, such as project development activities, but split between a central company and external partner(s) such as contractors.
- **Between-stage interdependence:** It refers to the level of interdependence of activities carried out in different stages of the project. More precisely, it refers to situations where activities performed at an early stage of project development affect other activities performed at later stages (such as the effect of design activities on production activities).

To conclude about the importance of considering interdependencies between project elements, we cite here a research study which was conducted during my internship in another context (project risks) and presented in 2018 in the 21<sup>st</sup> edition of Lambda Mu Congress "Risk management and digital transformation: opportunities and threats" (Marle et al., 2018). The paper is included in Appendix 3.

The general question was « Does the advanced analysis considering interdependencies allow a better anticipation of project's behavior than the classical analysis conducted without considering interdependencies? »

To illustrate this research, two risk analyses were conducted in 2014 and 2017. The approach was first to analyze the risks estimated in 2014 according to the basic principles (based on probability and impact), and then according to the advanced principles (based on the risk interdependency matrix). For both analyses, a comparison was made with the actual 2017 values, in an attempt to provide answers to the following two questions:

- 1/ does the advanced analysis from 2014 better anticipate the actual condition in 2017? And if so, is it a general improvement or specific to certain areas of the project, certain types of risks?
- 2/ does the advanced analysis allow for better selection of actions to put into the risk management plan?

When the paper was submitted, some developments were still in progress, but the first results were promising. Details are in (Marle et al., 2018) in Appendix 3. As a wrap-up, results showed a significant improvement in predictive ability in complex cases, where the density of the network is the highest. In addition, considering the complex nature of the risk network with the advanced analysis resulted in a significant correction of the risk management plan compared to that obtained with the basic analysis.

In our context, it is an argument for modeling interdependencies between decisions (and not risks), to get the same types of benefits which are better anticipation and better decision-making. A last argument is the similarity between the very nature of decisions and risks, since they are both related to:

- heterogeneous objects: decisions and risks may be related to all project dimensions, including product, process, and organization (Marle & Vidal, 2016)
- the concept of event: there is one moment when the risk occurs, there is one moment when the decision is taken. In both cases, the project trajectory forks.

It is thus important to analyze how decisions are made in projects, individually or as a set. This is the object of the next section.

## 2.3 Decision-making in complex projects

In this section, related work on decision-making in complex projects is provided, including the definition of project management and generic issues associated with single decision-making.

### 2.3.1 Managing a project is mostly making decisions

The management philosophy was essential to meet the challenges that organizations and companies face. It refers to all the leadership, managerial, and organizational techniques used in the execution of a project to achieve a specific result which must satisfy the triplet "cost", "time", "quality". The following definition is stated according to Project Management Institute (2013).

#### **Definition**

Project management is the application of knowledge, skills, tools, and techniques to project activities to meet the project requirements (PMI, 2013)

In other words, project management refers to the process of managing the activities of a team to achieve project objectives under the given constraints. It has emerged as a structured and formalized discipline from several fields of application, notably the construction industry, engineering, and heavy defense activities. It was first officially recognized in the 1950s as a separate discipline from management discipline (Cleland & Gareis, 2006).

This enabled challenges such as increasing competition, faster time to market for products and services, globalization, social, political, economic and technological transformations to be addressed (Cleland & Gareis, 2006). Subsequently, project management has been extended to different specialties, organizations, and countries.

Various methodologies or management models are nowadays available that implement different principles and standards. These methodologies can be classified into two categories: the first includes so-called traditional methods such as the Work Breakdown Structure (WBS), the Evaluation and Review Technique (PERT), networks, decision trees, matrices, the V-cycle method, etc., while the second includes those that are part of the agile dynamic such as the Scrum method, the Kanban method, etc. They all rely on a series of decisions followed by an execution of these decisions, notably with activities.

### 2.3.2 Generic issues associated with single decision-making

“Making a good decision involves making trade-offs between multiple objectives to select an alternative that best meets the values of the decision maker” (Delano et al., 2019). However, this may seem more difficult when the degree of uncertainty is high, the alternatives are not sufficiently clear and there are not enough alternatives to select from. In fact, when the alternatives and their consequences are clear and obvious, it makes for a quick and easy decision (De Jesus et al., 2019).

However, in complex projects such as upstream development projects, this may not always be the case since it is more common to face situations in which the alternatives and their consequences are not clear. This may explain why slow decision making is found to be one of the factors related to decision making that affects project effectiveness (Niayeshnia et al., 2020).

Additionally, nearly everything in our real world is interdependent. This also applies to decisions in projects, as most of them get affected by those that have been made before and by those that will be made at later stages (Formoso et al., 2002).

This leads to more difficulties in decision making as each decision influences and can be influenced directly or indirectly by other decisions.

Decision making is an essential part of project management. In any organization, there are situations that require decisions to be made to overcome problems. To improve decision making, it is important to be clear about the definition of "decision" and second what it does mean a decision making. Historically, the term "decision" originates from the Latin "*decisio*" meaning "a settlement, an agreement". For the English meaning of the word decision, the Cambridge dictionary defines decision as "a choice that you make about something after thinking about several possibilities". In the decision theory literature, there are multiple definitions incorporating different characteristics of a decision. Among those definitions, some are provided in this section. The main characteristics of a decision are presented here.

According to Howard, a decision is a choice between several alternatives that involves an irrevocable allocation of resources (Howard, 1966). This means that once the decision is made, it is impossible or extremely expensive to return to the pre-existing situation. Some decisions, such as the construction of an offshore platform or the development of a well, are clearly irrevocable.

As stated by Ullman (2001), "a decision is a commitment to use resources" (Ullman, 2001). According to the SPE, a decision is "an action within the participants' control that usually comes with a commitment of resources to execute an action (but could also be an agreement to do nothing)" (SPE Technical Report, 2015). Indeed, when a decision is made, one of the alternatives is chosen. Thus, the future workload, based on the chosen alternative, uses time, money, and other resources.

The OMG adopts the following definition: "a decision is the action of determining an output value (the chosen option), from a number of input values, using a logic that defining how the output is determined from the inputs" (OMG, 2019). As for Stal-Le Cardinal, she defined a decision as a process that leads an actor to answer a given question (Stal-Le Cardinal, 2000).

These definitions may seem interesting in some contexts, but they neglect an important notion in projects: the interdependencies between decisions. A more inclusive definition has been proposed by Jaber (2016), and it will be retained in this thesis:

#### **Definition of a decision**

"A choice made by one or more human beings among several alternatives. Each decision is based on choice criteria and requires certain information. It has consequences, positive or negative, on the object in which it is related to, or to other external objects" (Jaber, 2016).

Thus, as we can clearly infer, single decision making is itself a real challenge, which raises concerns for multiple decision making. This is the object of following sections to describe research gaps and questions.

2.4 Research gap #1: the need to formalize interdependencies between decisions

According to the *Centre National de Ressources Textuelles et Lexicales* CNRTL, interdependence refers to a reciprocal relationship of dependence between two or more things or sets of things, phenomena, or persons. It designates the state of things that depend on each other. In accordance with Sorenson (2003), which defines interdependence in the context of organizations, interdependence refers to the extent to which at least two activities interact to achieve a common outcome (Sorenson, 2003). Galbraith (2014) has also defined interdependence in the context of organizations as “a variable that can be changed and can lead to different amounts of coordination” (Galbraith, 2014). From this definition, we can deduce that the type of interdependence conditions the form of coordination that will be adopted.

As any complex system, a project includes a variety of interdependencies between its different objects. As discussed in sub-section 2.2.3, these interdependencies constitute the core of the complexity of a project. Therefore, the management of interdependencies is a vital function for any organization (Tee & Davies, 2012). Unfortunately, given the large number of these interdependencies, it becomes extremely difficult to manage them with traditional project management methodologies such as Work Breakdown Structure (WBS), Program Evaluation and Review Technique (PERT), decisions lists, and Gantt chart (Vidal, 2009).

For instance, “the WBS and Gantt chart are challenged by their inability to manage the entire problem of complexity and interaction in and around a project” (Jaber 2016). Consistent with the above, El-Reedy argued that the interactions between all activities are not adequately reflected by the Gantt chart (El-Reedy, 2016). An example of a work breakdown structure (WBS) for an oil and gas project is provided in the following Figure 12.

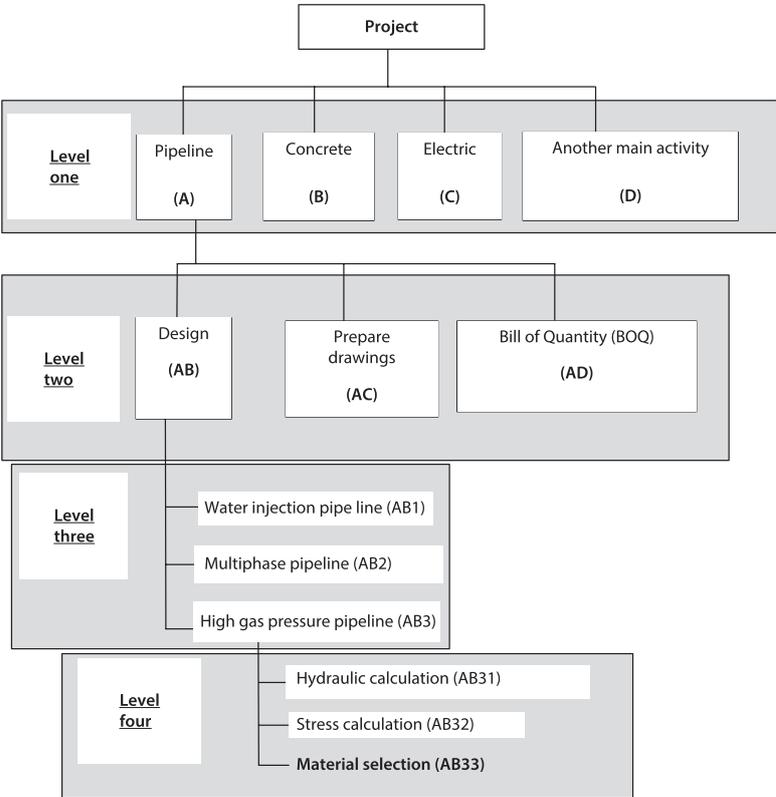


Figure 12: Example of a work breakdown structure (WBS) for an oil and gas project, source (El-Reedy, 2016)

This suggests that the reality of the complexity of the relationships between the different elements of the project may not be adequately captured by traditional methods and tools. In examining the causes of this failure, we found that decomposing the elements of a complex project into independent units is not effective because it does not allow to properly model the interdependencies that exist between these elements (H. Jaber et al., 2018).

Given the large number and variety of interdependencies between project elements, including decisions, it becomes challenging to fully understand, manage, and control project behavior. In the literature, several authors have studied how to successfully manage interdependence in organizations (Tee & Davies, 2012). Indeed, existing research has provided interesting insights into how to manage interdependence among the different elements of a project, such as activities, risks, deliverables, stakeholders, product components, but some important questions remain. Studies on the interdependence of decisions are still limited.

Managing interdependencies in large-scale projects is crucial to their success, notably because the amount of interdependency is correlated with the size of a system with a nonlinear ratio (square). Oil and Gas development projects are characterized by different development phases, each of which requiring the collaboration of multiple actors from multiple disciplines. Such collaboration is essential to ensure the smooth running of the project. However, this implies challenging decision making as multiple interdependencies must be identified and properly managed (Flanagan et al., 2008).

Thus, decision making in a highly interconnected project becomes more challenging as the number of interacting decisions increases. This prompted Flanagan and co-authors to advocate the need for developing more reliable methods for identifying and managing dependencies in oil and gas projects, as traditional project management techniques based on discussion processes are ineffective in a complex environment (Flanagan et al., 2008).

Therefore, we argue that one key to the quality of a set of decisions is the ability of decision makers to understand the interdependencies between decisions and anticipate their direct and indirect impacts. Continuing in the same vein, Killen is convinced that to successfully manage decisions in a complex project, their interdependencies and thus impacts on other decisions need to be analyzed and integrated into the decision-making process (Killen, 2007). It is important to be aware of the impact of the choices made and to ensure that the decisions taken do not generate undesirable or unexpected effects in the future.

In complex systems, the decision maker's ability to identify the interdependencies between decisions made within and outside their discipline as well as their effects is limited (Tergan & Keller, 2005). Sometimes, decision makers do not realize that their decisions can have dramatic consequences on other decisions in their direct or indirect environment.

The increasing complexity in firms and their projects has led to the need to develop advanced and more collaborative methods to handle this complexity, notably its potential impact on decision making in the field of oil and gas projects. Indeed, these projects must respect strict budgets and demanding schedules that do not always match reality (Elhoush & Kulatunga, 2017; Merrow, 2012). The constrained time horizons can negatively affect decision-making ability, as they put pressure on decision-makers who are forced to make decisions simultaneously considering several targets and huge amounts of information.

However, as widely known, decisions made under time pressure are likely to be made without serious evaluation of all possible alternatives and suffer quality and robustness loss (Edland & Svenson, 1993). As a result, making decisions in a complex project can be constrained by the human cognitive capacity to handle and analyze multiple sources of information in a limited time. This phenomenon was highlighted by Killen, particularly for project portfolio management decisions (Killen, 2007).

Actors in construction projects, and particularly in oil and gas projects, process massive amounts of information from a variety of stakeholders, such as engineers, designers, contractors, subcontractors, suppliers, governments, financial institutions and local authorities (Alaloul et al., 2016). Another major challenge in such projects is that development studies and data acquisition are costly and may require years to complete (Kafisanwo et al., 2018). So, it is difficult to gather all the necessary information as some of the information can be very costly or time consuming. This, in turn, puts pressure on policy makers to make decisions with potentially incomplete and inaccurate information (Killen, 2007). Moreover, design decision making is an intensive exercise, as these projects are usually technically complex.

Oil and Gas companies operate in inaccessible or difficult areas and under severe environmental conditions to extract hydrocarbons (Mehrotra & Gopalan, 2017), and their design activities are highly dependent on reservoir location (Salama et al., 2008). They also must deal with oil and gas's geopolitical and economic vagaries. They are uncertain and risky given that geoscientific uncertainties are considerable and subsoil resources are only known at the end of the field's life. Other risks that can affect the successful completion of a project, in addition to geoscientific uncertainties, include accidents, price fluctuations, unsuitability of materials, meteorological conditions, the international situation, and environmental, health, and safety conditions (S. X. Zeng et al., 2015).

These factors can contribute to the fact that some decisions are made without considering their potential direct and indirect implications at the time of the decision. As a result, many decisions made later in the process may have a greater or different impact than originally anticipated. There is also some uncertainty about the decision to be made, about the parameters of the project environment, but also about the consequences that this decision has on other directly or indirectly related decisions.

Another challenging aspect is that these projects involve multiple and diverse stakeholders to accomplish the megaproject, coming from different fields, organizations, and located in different countries, including the operating company, political actors, contractors, subcontractors, suppliers, partners, host countries, and non-governmental organizations (Eweje et al., 2012; Ventroux, 2015; Zarei et al., 2018). They have to deal with organizational problems since these projects require the collaboration and coordination of actors from different domains and coordination that crosses traditional organizational boundaries (Merrow and Analysis 2012; Salama et al. 2008).

Consequently, numerous interdependent decisions are made in such projects to satisfy their objectives. This leads us to mention another factor no less important than the previous ones, namely the interdependence of decisions. Thus, the complexity of decision making is enhanced by the interdependencies between decisions, which must be managed with other considerations, such as financial, political, environmental, uncertainty, risk, resource constraints and other factors. These interdependencies can lead to interactions, unpredictable consequences in the project or, as already stated, different from those initially planned.

Additionally, interdependencies of decisions may prevent choosing the combination of the best alternatives since those are incompatible. That induces a high degree of complexity and a high level of risks in resolving these decision-making issues (Shafiee et al., 2019). According to Sweeney and co-authors there is a contradiction between the technical requirements for making reliable and robust decisions and the managerial requirement of making them as fast as possible with an "as light as possible" process (the KISS "Keep It Simple Stupid" culture).

### **Research gap #1**

In this environment of complex Oil and Gas projects, problems can arise in managing decisions, their interdependencies, and the actors involved in these decisions.

There is a lack of a deep approach to decision-making in complex environments that considers the interdependencies between decisions.

## 2.5 Research gap #2: the need for coordination between interdependent decisions

The definition of coordination theory in its theoretical context is referred as " a body of principles about how the activities of separate actors can work together harmoniously" (Malone & Crowston, 1993). Coordination also has a more usual meaning than the one it has in its theoretical context. Different definitions are available in the literature, but we will first present the meaning of coordination from its intuitive meaning. Indeed, for each of us, we might have an intuitive understanding of its meaning since we can all experience different situations involving good or bad coordination in our daily lives. When we witness a victory of a soccer team or another collective sport, a fluid dance performance, or a successful musical performance, we may notice that the movements, the actions of the group of people seem well coordinated and synchronized. The effect of poor coordination can also be quickly identified. For example, a lack of coordination between two skaters during a skating performance can be easily recognized because it leads to a total failure. Thus, coordination can be experienced in many types of systems: human, communicational, biological, projects and others.

We proceed now to its formal definition as defined by practitioners and researchers. It is most useful to begin with the basic definition of coordination taken from the Cambridge dictionary as follows: "the act of making all the people involved in a plan or activity work together in an organized way". Based on this definition, we can understand that actors are an important part of the coordination process and thus coordination can only occur when multiple actors are involved. However, for Malone and Crowston, coordination can occur even if there is only one actor carrying out all the activities. The key element in coordination is rather the interdependence between the activities.

Therefore, they define coordination as "the act of managing interdependencies between activities performed to achieve a goal" (Malone & Crowston, 1990, 1993). A more recent study defines coordination in an inter-organizational context, such as oil and gas projects as the way stakeholders synchronize, align and adjust their activities to carry out their interdependent tasks and achieve their common goals. (Gulati et al., 2012). Given these two definitions, we can conclude that coordination can be seen as the process of managing dependencies among activities. For our context, we define coordination as the following.

### **Definition of coordination**

Coordination is defined as the way in which actors synchronize their interdependent decisions to achieve their collectives and individual objectives.

This definition includes three key elements associated with coordination processes, namely goals, decisions and finally the interdependencies between these decisions.

In this work, the emphasis is on the coordination of decisions in complex projects such as oil and gas projects. Such interest arises since many studies have shown a strong relationship between the coordination process in general and the success of construction projects (Alaloul et al., 2016). More specifically, it depends on the effective coordination of the contributions of the multiple project actors (Bygballe et al., 2016), including their interdependent decisions and activities needing to be effectively synchronized, aligned and adjusted.

In particular, oil and energy projects involve a variety of complex activities performed by multiple stakeholders throughout the project life cycle, including engineering, procurement and construction, and their success requires careful coordination (Niayeshnia et al., 2020). The coordination of decisions has been addressed by various authors in different industrial fields, including oil and gas development. This attention is because one of the main factors guaranteeing success in the early phases of development is an effective and continuous coordination effort (El-Reedy, 2016). However, the coordination of decisions taken during the project may also be complex (Ventroux et al., 2017), especially the initial ones since they structure what can be done in the future and condition the success or failure of the project.

Moreover, to ensure effective coordination, certain conditions must be met, such as harmonious interaction between the actors. According to Society of Petroleum Engineers report, coordination is the key to ensuring decisions' quality, rapidity, and efficiency (SPE Technical Report, 2015). Failing to ensure timely and synchronous coordination of decisions can dramatically affect project execution. Among the studies that attempted to propose solutions to this problem, we can cite the work of Jaber and co-authors (H. Jaber et al., 2018). They proposed to group actors based on their relationships as a result of their assignment to decisions.

Indeed, it is obvious that good coordination of actors inevitably leads to good coordination of project decisions, since these actors are assigned to the decisions. In fact, the coordination of project actors in the construction industry, unlike the coordination of decisions, has drawn the attention of both practitioners and researchers since the late 1980s (Cicmil & Marshall, 2012).

Moreover, to improve the coordination of multiple decisions, Lederer and co-workers (Lederer et al., 2010) proposed using a cross-decision matrix that allows decision-makers to visualize possible dependencies between decisions at a given point in time and gain a better understanding of their impact. The consistency of certain decisions, especially those that must be taken collaboratively, and the control of their impacts can also pose a significant problem in managing such projects. Coordinated and thus consistent decisions are crucial to the success of a project. One study recently showed that factors related to these two elements influence the project's progress. These include changes in decisions, slow decision-making, quality of decisions, poor communication between stakeholders, design inconsistencies, and mistakes (Niayeshnia et al., 2020).

Another study also pointed out that one of the main causes of delay in oil and gas projects is the slow decision-making process (Zarei et al., 2018). Chacon and co-authors have stressed the importance of ensuring coherence and consistency of decisions in oil and gas projects (Chacón et al., 2004), particularly for operating a production network. Coordination is essential to ensure coherence and consistency of decisions (Chacón et al., 2004). A robust decision-making concept in engineering design is developed by (Ullman, 2001). It includes 12 steps necessary to make robust decisions. This process focuses on generating decision alternatives and developing criteria for evaluating them. It helps make one decision at a time. However, it offers little help for improving coordination among multiple decisions. It does not describe how to ensure compatibility between decision alternatives or manage dependency between them.

### **Research gap #2**

Projects in the Oil and Gas industry still suffer from inefficient decision making, leading to potential delays, conflicts, and losses. Currently, there is no clear understanding of how to support decision makers in making multiple decisions in a coordinated manner or how to improve the compatibility of decisions.

## 2.6 Research approach

In our field, it is recommended to be as close as possible of fieldwork, that is why we chose to use a constructivist approach (Mäkinen, 1999), notably a Design Research Methodology-based approach, with alternation of prescriptive and descriptive study (Blessing & Chakrabarti, 2009; Laurel, 2003).

Mäkinen proposes in the following Table a 4-quarter classification for research.

*Table 5: the 5 families of research approaches by Mäkinen (1999)*

	Theoretical	Empirical
Descriptive	Conceptual	Nomothetic
Normative	Decision-oriented	Analysis-action Constructivist

The constructivist approach aims at building a specific solution to an explicit problem. It is based on the pragmatic principle and the belief that the deep analysis of a practical situation can lead to a theoretically significant contribution. The results are evaluated according to the double angle of novelty and applicability.

We place ourselves within the framework of this approach for two reasons. First, the difficulty of making a purely theoretical resolution of such a situation, as it involves humans. Second, the desire to prescribe things anyway, and not only to describe them.

More precisely, Design Science studies artificial artifacts and involves a research process to discover an effective solution to a problem (Simon, 1981). According to March and Smith, the Design Science approach includes 4 main activities (March & Smith, 1995):

- Build,
- Evaluate,
- Conceptualize,
- Justify.

The general idea of the Design Science approach is to create a better solution than what existed before. It has been used in the field of Business, Industrial Engineering or Management, as well as in Information Systems (Hevner et al., 2004). According to Simon (1981), the abstraction and representation of means, goals, and laws describing the phenomena are crucial, but require an iterative approach, often described as a spiral. It tends to adapt to the situation, by being iterative and collaborative, and starts from a proposal for action to go towards an abstraction and a proposal of alternative solutions that will be confronted with the initial request, and will eventually contribute to clarify it, to modify it, thus leading to a second round of proposal, etc.

The knowledge and understanding of a problem and its solution is therefore achieved through the construction and implementation (or testing) of these solutions (objects, artifacts, or immaterial constructions). Of course, the steps related to the field confrontation, whether it is to collect needs, ideas, or to test our models, processes, and analysis tools, are dependent on the activity of the company and on the relevance at the moment of the missions with regard to the research project.

In our case, we defined the following phases: a field diagnosis, interviews, formulation of the industrial problems faced, literature review, proposal of new concepts, industrial test and eventually validation. We started by carrying out a field diagnosis to understand the industrial problem, and in parallel we carried out a literature review. The diagnosis of the field was based on two elements: internal documents and internal interviews. Since the beginning of my thesis, a reading and analysis of internal working documents has been performed. They include Unidocs, Manual Guides (GM), Directives (DIR), and Company Rules (CR), etc. This reading was necessary to have a comprehensive and complete view of the decision-making mechanisms within TOTAL E&P. Overall, the objective of this phase was to map, from a documentary perspective, what happens at TOTAL in the development of its Exploration and Production E&P projects.

Then to further develop my investigation and better comprehend the different challenges related to decision making in our context, I opted to conduct a qualitative research method consisting of interviews with key actors from different disciplines involved in the decision-making process. So, a questionnaire was developed for these actors which include Project Managers, Architecture Manager, Procurement and Equipment Manager, Global Category Manager, Facilities and Engineering Manager etc.

The objective of this questionnaire was to understand how some decisions are made in practice, how their interdependencies are managed, and finally the way in which the notions of temporality and uncertainty associated with a decision are handled.

The literature review, presented in this second chapter allowed us to confirm our industrial problems and identify the gaps of research. This allowed us to identify a central research question, which was divided into two sub-questions. The literature review, presented in Chapter 1, allowed us to explore what was proposed in relation to our problem. Based on the literature and the knowledge acquired on our problem, we have formulated some proposals. These have been adjusted and approved during in-depth discussions with the industrial actors involved in this thesis work. Then to justify the validity of these proposals, we built a fictitious case study.

## 2.7 Chapter conclusion: Research questions and proposal

We can confirm from the literature that decision making in complex project is challenging and needs a new approach to handle such complexities. As confirmed by Iftikhar and co-authors in their recent research targeting megaprojects, these type of projects “would demand a more collaborative approach in decision making” and “a deep but at the same time rapid decision-making approach in megaprojects” (Iftikhar et al., 2022).

In addition, there is an identified need for better tools to understand and manage the interdependencies between decisions. We strongly believe that companies must be able to identify and manage these interdependencies so that decisions are no longer considered separately from other decisions in its environment. By doing so, appropriate decisions can be made.

Therefore, this doctoral thesis aims at proposing a decision-making process that considers the interdependencies between decisions, provides a clearer understanding of the possible impacts of decisions, and improves the consistency of multiple decisions by ensuring better coordination between the different actors involved in these decisions.

To address these issues, the main research questions to be answered are detailed in the following.

### 2.7.1 Research questions

We formulate the following overall research question:

**How to support decision makers in making multiple decisions in a coordinated manner?**

This can be divided into sub-questions: 1/How to ensure that the interdependencies between decisions are properly managed? 2/ How to support decision-makers in making multiple decisions in a coordinated manner and improving the compatibility of those decisions?

## 2.7.2 Research Proposal: a 3-block process for formulating, structuring, and solving the multi-decision problem

As shown in Figure 13, the proposed process is consisting of 3 blocks, namely problem formulating, problem structuring, and problem solving, which correspond to Chapter 3, Chapter 4, and Chapter 5 respectively.

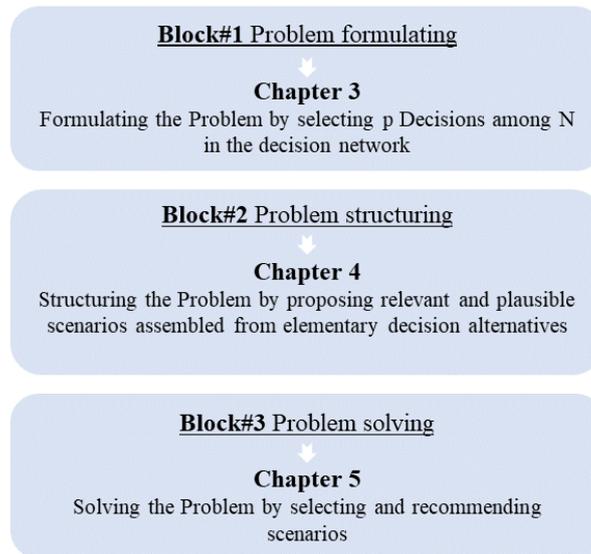


Figure 13: Complete process consisting of 3 blocks

Given the diversity of oil and gas development project contexts, we have proposed a multi-entry process. At each block, the decision-maker selects from a set of possible choices to adapt the decision-making process to the precise context:

- The first choice consists of selecting the formalism used to model the decision network.
- The second choice is about the possible simplification of the network.
- The third choice is to define the scope of modeled decisions and which of them will be taken at the end of the process, with several possibilities: making  $P$  decisions among  $N$  (general case), making one decision among  $N$  or making all decisions simultaneously.
- The fourth choice is to consider compatibility and performance simultaneously or sequentially.
- The fifth choice is to use absolute evaluation methods, complete comparison methods, or comparison to reference point methods.

In the following chapters, details about the complete research approach will be provided, where three propositions will be outlined and discussed.

3 Chapter 3- Formulating the Problem: making  $P$  decisions considering  $N$  decisions ( $1 \leq P \leq N$ )

This Chapter introduces the need and relevance of network modeling for interdependent decisions, thus the two main ways to model networks, respectively graph and matrix formats. This initial global network may have to be simplified, depending on its initial complexity and the requirement or capacity of decision-makers. Finally, the problem is formulated, to determine the  $P$  decisions which will have to be made among the  $N$  interdependent decisions which are considered. “Considered” means that the impact of the  $P$  decisions on the  $N-P$  other ones will be considered, albeit no final decision will be made on the latter. This means that from an initial network with  $M$  decisions, only  $N$  decisions are considered in input, and finally  $P$  decisions are taken in output.

### 3.1 Chapter introduction: the need for building first a global decision network to formulate a local multi-decision problem

This section introduces the Chapter by defining interdependency between decisions, giving elements about how to quantify them, and finally showing how to assembly them in a weighted decision-decision network (also called decision network for the sake of reading simplicity).

#### 3.1.1 Our definition of interdependency between project decisions

As previously discussed, a high diversity of objects characterizes a project (Marle, 2002): deliverables, objectives, activities, actors, risks, components, and decisions. Each object is defined by a set of attributes (Vidal, 2009). Among these objects, we study in this Ph.D. work decisions and some of their attributes. The focus on decisions is due to their important role in oil and gas projects. They influence the execution of various activities, from the most basic to the most critical, such as the selection of contactors, the choice of contracting strategy, the design of the production platform, and its implementation and production process.

Decisions, labeled here  $D_i$  (where  $i \in \{1...M\}$ ), are characterized by decision alternatives, among other attributes (Ullman 2001). These alternatives are designed here by  $D_{ij}$ , where  $D_{ij}$  is the  $j^{\text{th}}$  alternative for decision  $D_i$  (the number of alternatives for each decision is not known in advance).

According to (Marle, 2002), a project object is a material or immaterial element interacting with other objects. This then implies that decisions have interdependencies, between them and with other objects (not in the scope of this PhD).

Considering that decisions  $\mathbf{D}_1$  and  $\mathbf{D}_2$  are related means that the output of decision  $\mathbf{D}_1$  may have an impact on the remaining possible alternatives for  $\mathbf{D}_2$ . The output means the result of the choice process between decision alternatives, not the result of the execution of this decision alternative.

This last point (the actual result of the execution of selected alternative) may also have an impact on other decisions. For instance, an over cost in the execution of  $\mathbf{D}_1$  may have an impact on the remaining budget, thus on remaining possible alternatives for  $\mathbf{D}_2$ . However, this is not in the scope of this Ph.D., we are ahead of execution of decision alternatives.

### 3.1.2 The quantification of interdependencies between decisions

The quantification of interdependencies may be binary or numerical, with qualitative or quantitative assessment. For the binary quantification, the value “1” indicates the existence of interdependency between two decisions whereas “0” indicates the absence of interdependence.

To have more precision, numerical values can be attributed to quantify these interdependencies. This type of quantification is useful as it helps to understand the strength of the interdependencies and thus estimate properly their impact on decision-making.

These numerical values can be estimated by experts by using a verbal scale that allows to differentiate the different levels of interdependence (Yassine, 2004b). For instance, a discrete scale with 4 levels of interdependence can be defined: 1= low dependence, 2= medium dependence, 3= high dependence, and 4= very high dependence. Thus, a discrete scale of five levels of dependence ranging from 1 (weak) to 5 (strong) was also used in another context to estimate risk interdependencies (Kilani & Marle, 2019b).

In other contexts, relative pairwise assessment has been done, using AHP for instance (Marle and Vidal, 2011a).

Whatever the method, collecting data on the interdependencies between these decisions is simultaneously a challenge and a critical factor in the robustness of the analyses. This task can be time consuming as this type of data is neither existing (from past projects) nor easy to obtain (Browning, 2001).

The consequence of interdependency weighting may be a different color or value in a matrix or a different edge thickness and/or color in a graph.

In this Ph.D. work, we consider the interdependency assessment method as an input since we were not able to know how the company would practically do this in its projects.

### 3.1.3 The usefulness of network modeling for interdependent decisions

We argue that network modeling can be a useful tool to help better understand and manage interdependencies. Indeed, according to Keller and Tergan (2005), the use of visualization tools in general, such as networks, can be an effective way to support users in dealing with complexity.

In particular, it helps overcoming any limitations related to the ability to recognize and represent the interdependencies between elements of a complex system (Tergan & Keller, 2005). In our context, the nature of the oil and gas project provides favorable ground for the use of networks, as they involve numerous and various actors and objects interacting and communicating (Zarei et al., 2018).

Killen has specifically chosen to model project portfolio management decisions because they "are subject to the limits of human cognitive ability to analyze a variety of information in a limited time" (Killen, 2007). She has used a "visual project map" method, which is known as a method for implementing network mapping approaches to project portfolios to enhance the ability to understand the interdependencies between projects. The following Figure 14 shows an example of a portion of a visual project map. The labels indicate the project name, the required investment, and the value of the NPV. Circle size reflects the investment required.

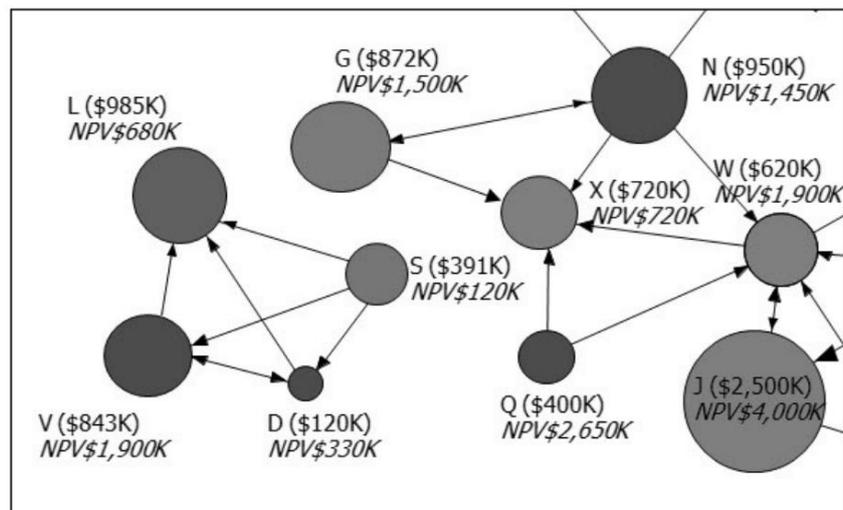


Figure 14: An example of a portion of a visual project map, source (Killen, 2007).

The following paragraphs discuss related work on graphs and matrices as tools for modeling complex systems.

## 3.2 Modeling the global project M-decision network

In this section, related work on modeling the project decision network is provided, including graphs and matrices. An intermediary conclusion about the modeling choice is then proposed.

### 3.2.1 Graphs

To model the complexity of systems, it is possible first to use graphs, recognized as a useful way to manage a high number of elements and interdependencies. In the following, we present a review of this method and discuss some of its applications in oil and gas contexts and in other contexts.

#### 3.2.1.1 The generic concept of graph

Graph is a modeling tool that allows to model complex systems. Graphs have emerged as a useful tool to represent the relationships and dependencies between the components of a system (Kilani & Marle, 2019b). A graph can be constructed by modeling each element of the system (a project for instance) by a node and a relationship between two elements of the system (or project) by a link (or an edge) connecting two nodes (Yassine, 2004b). The links between project elements may follow a certain direction indicating how one element affects another. This requires special attention when analyzing interdependencies, since a misdirection can easily reverse the meaning of the link.

Graphs are used for a long time in multiple contexts. They have been used for example to model project elements such as risks (Fang et al., 2010; Farahani et al., 2021), deliverables (Jaber et al., 2018), tasks, stakeholders (Alhammadi, 2021; Feng & Crawley, 2009; Gondia et al., 2022; Moussa & El-Dakhakhni, 2022), and decisions (Gaspars-Wieloch, 2017; OMG, 2019).

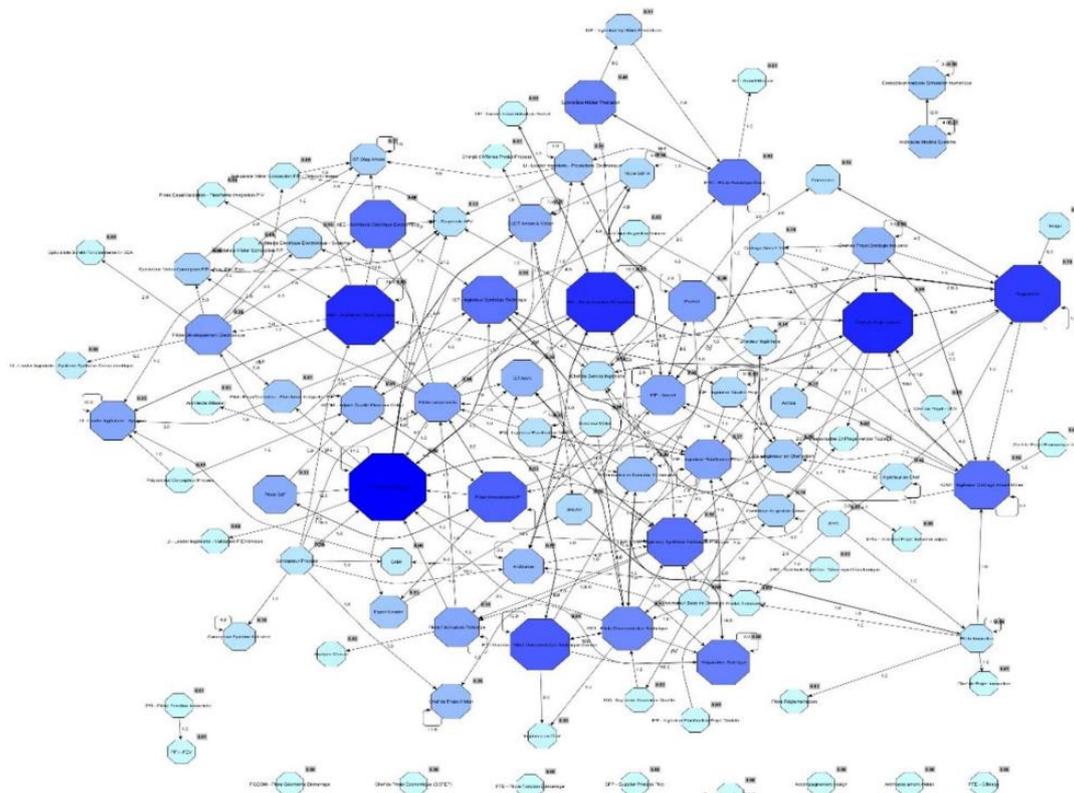


Figure 15: The network of direct relationships between the project actors, source (Jaber 2016)

In the context of infrastructure projects, the interdependence between contractors and subcontractors has been quantified through two types of networks: a dynamic network (e.g., monthly) and a static network (i.e., a complete project). In this network, the nodes represent the contractors, and the weight of the links represents the extent of their interdependence (Gondia et al., 2022; Moussa & El-Dakhakhni, 2022).

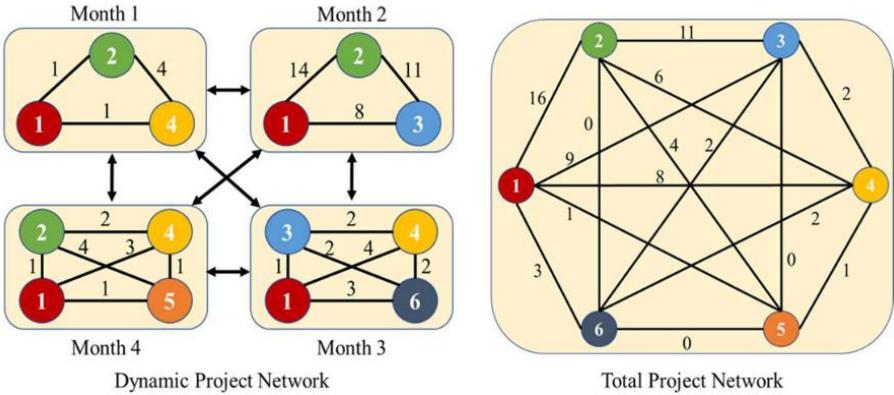


Figure 16: example of two types of contractor interdependence networks, source (Moussa & El-Dakhakhni, 2022)

3.2.1.2 The existing applications of graphs in oil and gas context

It is important to highlight that graph theory has been widely used in the context of oil and gas development projects as they “involve various stakeholders and actors, and multiple nodes and factors that interact and communicate within interwoven networks” (Zarei et al., 2018). The application in this field was conducted for different reasons.

According to Zarei and co-authors, Semantic Network Analysis (SNA) has been applied in this context as these projects are characterized by multiple nodes and elements interacting within tightly interconnected networks (Zarei et al., 2018). As shown in Figure 17, a network of the projects and their interrelationships has been used to analysis delay causes in projects in the Oil-Gas-Petrochemical (OGP) sector.

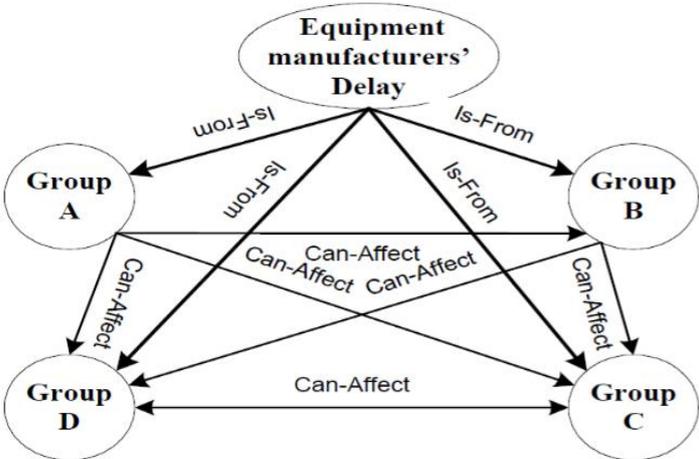


Figure 17: An example of Semantic network of delay causes, source (Zarei et al., 2018)

It was also applied to model and assess the challenges that prevent successful execution of sustainability strategies in Qatar's Oil and Gas industry (Sarrakh et al., 2022).

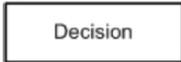
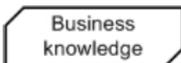
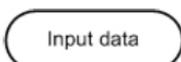
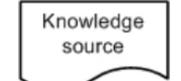
The Bayesian Network (BN) consists of a probabilistic graphical model allowing to model the interactions between different elements as a directed acyclic graph. It has been used in many fields, notably in the oil and gas industry. For instance, they have been used to model the risk of piracy affecting oil platforms (Bouejla, 2014) and to assess the probability of corrosion of oil and gas pipelines (Ayello et al., 2014).

This type of graphical modeling has provided a valuable aid, allowing the interdependencies between network elements to be modeled. This modeling allows for decision support under uncertainty and more informed decision making (Guarnieri et al., 2014). Nevertheless, these networks are not relevant to our problem, as they require more statistical expertise than other methods and we do not attempt to perform statistical calculations. Furthermore, as highlighted by Fang and Marle, they fail to model cyclic events as loops are not allowed, which can potentially cause problems in real projects (Fang & Marle, 2011).

*3.2.1.3 The existing application of graphs to the domain of decision-making*

However, studies on modeling project decisions using this approach are limited. According to the Object Management Group, human decision making can be considered as a network of interdependent elements, including sub-decisions (OMG, 2019). We detail here their work based on graphical structures to model decision-making. The objective was to provide a common notation easily understandable by all decision makers. In this type of presentation, the decisions, the elements that contribute to the decision-making, and their relationships are modeled. The notation and definition of all graph constituents are summarized in Table 6 below.

*Table 6: Notation and definition of the components modeled in the graph, source (OMG, 2019)*

Component		Description	Notation
Elements	Decision	A decision denotes the act of determining an output from a number of inputs, using decision logic which may reference one or more business knowledge models.	
	Business Knowledge Model	A business knowledge model denotes a function encapsulating business knowledge, e.g., as business rules, a decision table, or an analytic model.	
	Input Data	An input data element denotes information used as an input by one or more decisions. When enclosed within a knowledge model, it denotes the parameters to the knowledge model.	
	Knowledge Source	A knowledge source denotes an authority for a business knowledge model or decision.	

Besides more than one type of link is suggested in this presentation. These links are classified into three types of requirements: information, knowledge, and authority. Each type is characterized by a specific symbol as shown the following Table 7.

Table 7: Notation and definition of the links modeled in the graph, source (OMG 2019)

Requirements	Information Requirement	An information requirement denotes input data or a decision output being used as one of the inputs of a decision.	
	Knowledge Requirement	A knowledge requirement denotes the invocation of a business knowledge model.	
	Authority Requirement	An authority requirement denotes the dependence of a DRD element on another DRD element that acts as a source of guidance or knowledge.	

However, what the OMG proposes requires a significant effort to gather information. Once the interdependencies have been identified, we have to try to classify them according to the three types of requirements. In addition, different types of objects are modeled in the graph, which can make things difficult and may confuse the project actors. As stated by Browning, “flowcharts with all sorts of boxes and arrows ("spaghetti and meatballs") do not simplify the problem” (Browning, 2000).

Considering as an example the graph illustrated in the following Figure 18. It represents 30 elements and 46 requirements. Compared to other graphs, it does not look very large but can certainly seem difficult to manage and control for many decision-makers. In general, the construction of a single graph that represents the entire domain of decision making will be challenging, as the resulting graph would be difficult to manage and to work with (Campagna et al., 2020; OMG, 2019).

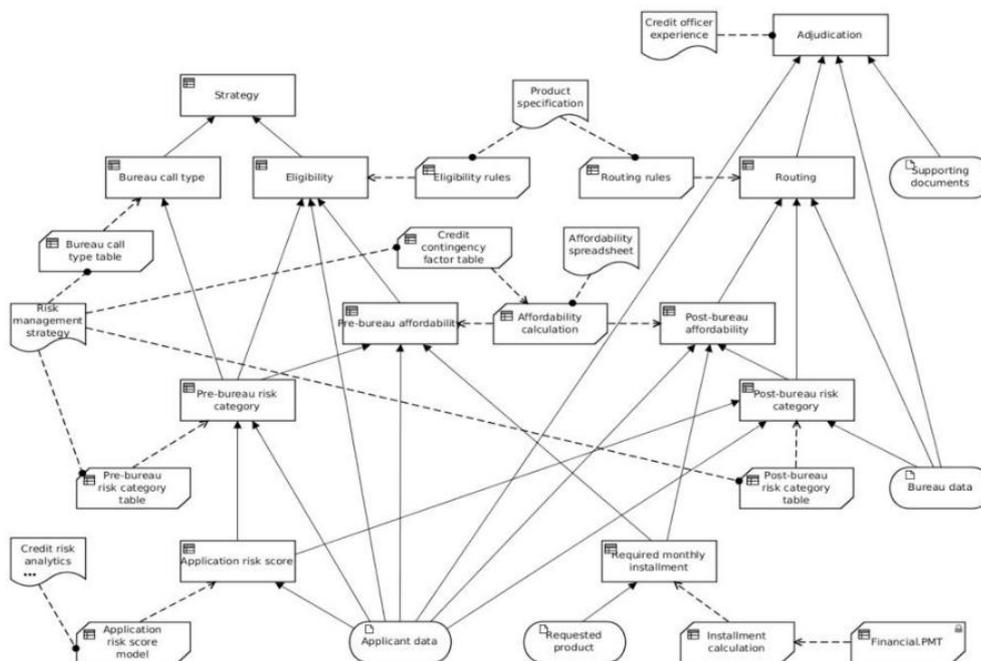


Figure 18: An extract of a decision making network, source (OMG, 2019)

### 3.2.2 Matrices

Matrices are another approach to modeling system complexity. In this section, we present a review of matrix-based modeling approach and discuss some of its applications, particularly in the oil and gas context.

#### 3.2.2.1 The generic concept of matrix

To any graph, we can associate a matrix called the adjacency matrix. This matrix symbolizes another type of presentation that models the interactions between the graph elements (Harary, 1962). An adjacency matrix for a finite graph with  $n$  nodes is a matrix of dimension  $n \times n$  whose non-diagonal element  $a_{ij}$  models the presence of a link between node  $i$  and node  $j$ . The following Figure 19 illustrates the adjacent matrix principle for 4 types of graphs, namely directed, undirected, knowledge and weighted graphs respectively. The edges of graph (A) are directed, while those of graph (B) are undirected. Graph (C) is a knowledge graph consisting of two different types of nodes represented by different colors and two different types of edges. Graph (C) is a directed and heterogeneous graph. Graph (D) is a weighted graph where all edges are weighted by a specific value. The corresponding  $4 \times 4$  adjacency matrices for the graphs from (A) to (D) are provided in the second row from (E) to (H).

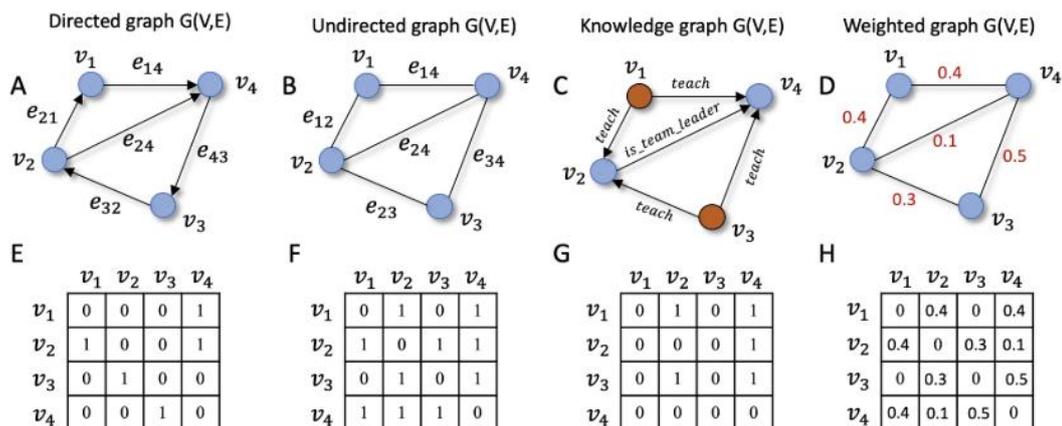


Figure 19: Graphs of different types and their corresponding representation in adjacency matrix, source (Xu, 2020)

The Design Structure Matrix (DSM), developed by (Steward, 1981), has proven to be a valuable tool for modeling and analyzing complex systems and their components (Xiao and Chen, 2010). In general terms, a DSM is a square binary matrix: "1" indicates the existence of an interaction, while "0" indicates the absence of interaction. It contains  $m$  rows and columns and  $n$  non-zero cells, where  $m$  is the number of nodes and  $n$  is the number of links in the corresponding graph (H. Jaber et al., 2015). For a more accurate description, it is possible to represent the strength of the interactions between the elements by using other appropriate values. It is static, which means that it shows the interactions between elements at a given time.

Among the project objects modeled using a DSM matrix are the following: product components (Algeddawy, 2014), groups of actors operating simultaneously on a project (Knippenberg et al., 2019), activities (Browning, 2000; Flanagan, 2007; Flanagan et al., 2008; Sharon et al., 2013; Welch, 2001), risks (Farahani et al., 2021; Marle & Vidal, 2011a), and decisions (Campagna et al., 2020; H. Jaber et al., 2015).

### 3.2.2.2 The existing applications of matrices in Oil and Gas context

Using the Design Structure Matrix (DSM) as a modeling tool has become extremely common in many research areas (Browning, 2001), including in the oil and gas industry. It has been applied in the context of oil and gas projects for multiple reasons. It was used, for example, to map the relationships between project stakeholders and improve their understanding (Alhammedi, 2021). It was also applied to an oilfield development project to improve its planning and execution. Results of this study showed that the number of design iterations and the project duration were significantly reduced (Gunawan, 2009). It helped determine the significant causes of rework (Flanagan et al., 2008).

It has also been applied to visualize the complexity and potential risks of the FPSO renovation versus a new construction option. A first matrix studied the propagation of changes resulting from this renovation, and a second one studied the interdependencies between the activities conducted for this renovation (Flanagan, 2007). According to this study, the use of matrices reduced exposure to rework and thus decreased the global project risk exposure. The first matrix is shown in Figure 20, the red color indicating a strong dependence, orange a medium dependence and yellow a weak dependence. The strength of matrices is illustrated in Figure 20, namely the ability to model many objects and interdependencies in a compact format.

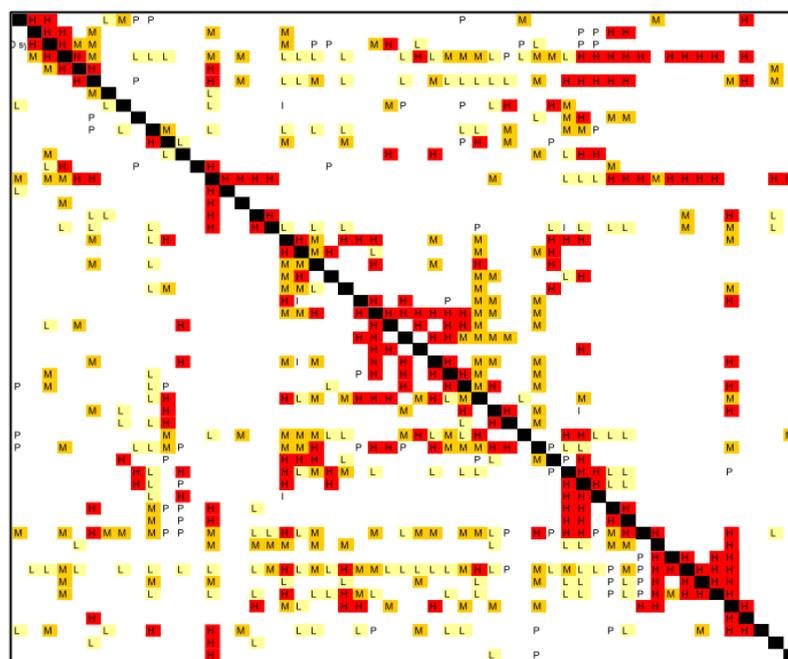


Figure 20: FPSO Change Propagation DSM, source (Flanagan, 2007)

Furthermore, it has been used in the early phases of offshore oil and gas projects to model facility connectivity and process flow, as block flow diagrams (BFDs) can provide an illustration that is difficult to read (Johnson, 2020).

DSM is therefore not a novelty in the context of oil and gas development, but as we have already seen, it is widely used in specific contexts within this field.

### 3.2.2.3 Application of matrices to the domain of decision-making

However, the use of DSM to model interdependencies between decisions is poorly studied in this context. Some studies have attempted to model the interdependencies between decisions using DSM but not in a particular field. Among those, we can cite the research of Lederer and his co-authors. They proposed modeling decisions using matrix approaches as those are a meaningful way to clearly understand their interdependencies at a given time (Lederer et al., 2010).

This type of modeling can help anticipate each decision's consequences, allowing the decision-maker to be fully aware of the consequences that may result from their decisions. That may help prevent surprises that can induce heavy backtracking, infecting the entire team. The following matrix, shown in Figure 21, illustrates an example of a binary matrix showing the interdependence of decisions and including both product and process decisions. The cell marked with a value of 1 indicates that there is a link of interdependence between the two decisions. Once the interdependencies are clarified, it is easier to identify the actors who need to work together and anticipate the different consequences that may arise (H. Jaber et al., 2015). That leads to a more efficient and fluid decision-making process thanks to the synchronization of decisions.

	Dprod,1	Dprod,2	Dprod,3	Dproc,1	Dproc,2	Dproc,3	Pprod,1	Pprod,2	Pprod,3	Pproc,1	Pproc,2	Pproc,3
Dproduct,1		1							1		1	
Dprod,2	1	1					1			1	1	1
Dprod,3				1	1			1		1	1	
Dprocess,1				1	1			1				1
Dproc,2		1							1	1		
Dproc,3	1						1			1		
Pproduct,1		1		1	1							
Pprod,2	1											
Pprod,3			1									
Pprocess,1				1								
Pproc,2	1				1	1						
Pproc,3				1								

Figure 21: Example of Decision-Decision Matrix, source (Lederer et al., 2010)

Campagna and co-authors proposed to model the global decision environment and not only the decisions themselves using the DSM approach, as dealing with graphs could be difficult, especially where a significant domain of decision making is involved (Campagna et al, 2020). This approach helps demonstrate the possible interdependencies between the different elements of a decision network (OMG, 2019). As depicted in the Figure 22, this environment comprises the essential elements for decision-making and the dependencies between them.

Such elements include a decision element, a Business Knowledge Model (BKM) element, an input data element, a knowledge source element, and a decision service element. The three requirements considered in his work reflect the dependencies between these elements: an information requirement, a knowledge requirement, and an authority requirement. Each matrix element is modeled with a different color, while different symbols represent the different requirements.



An overview of the main strengths and weaknesses of the two methods discussed in this subsection is given in the following Table 8. This table is assistance to make and justify the chosen methodology for managing the interdependencies of a complex system.

Indeed, for visualization for instance, the matrix format may be more suitable depending on the number of decisions to consider. On the other hand, if only one decision among N is going to be studied, the graph is probably more adapted, since when an element of the graph is zoomed in on, its direct environment and then its more distant environment can be clearly visualized.

Finally, it is also possible to combine the use of matrices with graphs, depending on the context (number of decisions and more than that interdependencies) and the situation (pure calculation, synchronous meeting, communication to a committee).

Table 8: Strengths and weaknesses of the two modeling methods studied

	Strengths	Weaknesses
Graphs	<p>Modeling of multiple nodes ranging from dozens to hundreds or even thousands (Marle, 2002).</p> <p>Capturing as faithfully as possible the real structure of the strong interdependencies between the objects of a system (Marle, 2002).</p>	<p>Visualizing complex and large graphs can be a major concern when dealing with systems involving multiple interdependencies and loops (Steward, 1981).</p> <p>The number and density of links must remain manageable and reasonable in relation to the capacity of the decision-makers</p> <p>Analyzing large-scale networks using conventional methods, including path analysis, connectivity analysis, and centrality analysis, can incur high computational costs and memory requirements due to the unavoidable difficult high dimensionality (Xu, 2020).</p> <p>Investigating the different interdependencies can be time consuming.</p> <p>Considering different types of interdependencies may be challenging to represent with edges (width, color, dotted lines...).</p>

<p>Matrices</p>	<p>Providing a more compact representation than graphs (Campagna et al., 2020; Yassine, 2004a).</p> <p>Providing more manageable visual support for complex networks. (Campagna et al., 2020; H. Jaber et al., 2018).</p> <p>Providing a consistent cartography between system elements that is clear and easy to read, regardless of its size. (Yassine, 2004a).</p> <p>Facilitating data analysis thanks to the calculations inherent to the matrix format (eigenvalues, matrix product and matrix transposition) (H. Jaber et al., 2018).</p> <p>Determination of the dependencies of a given element quickly (Campagna et al., 2020) via navigation through element row and column.</p> <p>Identifying feedback relationships is easier in the DSM than in the graph (Yassine, 2004a).</p>	<p>The number of nodes must remain manageable and reasonable in relation to the capacity of the decision-makers (matrix size n square).</p> <p>Investigating the different interdependencies can be time consuming.</p>
<p>Both</p>	<p>Enhancing visibility and awareness of the project's complexity (Yassine, 2004a).</p> <p>Providing a powerful visual tool to model, communicate and structure various types of data related to products and projects (Yassine, 2004a).</p>	<p>Requiring precise data not always easy to obtain, and a solid knowledge of the system studied (Browning, 2001).</p>

Once the initial decision network is modeled (with decision-decision interdependencies, also called D-D), an intermediary question, before specifying problem scope, is to know whether this model is manageable or not. This is the object of the following paragraph about network simplification.

### 3.3 Simplifying the M-decision network

Networks may contain hundreds or thousands of nodes and edges, which may decrease capacity to understand, analyze and make decisions. This Section tests the possibility to remove some elements in networks, mainly weak edges, to know if and how much precision is lost in terms of analysis.

Two real past networks have been studied to illustrate this research, albeit not in the context of this Ph.D., i.e., decision-decision network. That is why this Section is only here to present a future assistance to network simplification, but no test has been done for the moment in a real decision-decision network context.

A conference paper related to this Section has been presented in 2019 in the DSM Conference at Monterrey, CA (Kilani & Marle, 2019a). It is included in Appendix 4.

#### 3.3.1 The reason why simplification could be useful in our context

Visualizing and analyzing complex networks can be a major concern when dealing with projects involving multiple decisions, interdependencies, and loops. Whatever the scope of the system and of the project, there is always a choice of model boundaries. Decision network may thus contain hundreds of decisions and numerous links, which may decrease capacity to understand, analyze and make decisions. In addition, investigating the different interdependencies can be time consuming.

The challenge is therefore to have too much information and to encounter difficulties, both for the computer calculation and for the human understanding of complex networks. For these reasons, the number of nodes and edges must remain manageable and reasonable in relation to the capacity of the decision-makers. To overcome this problem, deciding to simplify the decision network can be helpful.

#### 3.3.2 Related work on network simplification

Different strategies are possible to simplify the decision network such as suppressing, compressing, compacting, clustering. Clustering will be detailed in section 3.4.1.

Different strategies are possible to group nodes or edges and compress or compact the network (Arenas et al., 2007; Blondel et al., 2008). The groups are renamed or called super nodes or super edges. Elements may be grouped because they are strongly connected, or because they are connected to similar elements. However, we are not in this case. We do not want to reduce the number of nodes, but to test the suppression of some edges. It is more related to importance measures of edges, or robustness of network behavior.

Some works have been done to study network disruption, notably in transportation (Murray et al., 2007), telecommunications (O’Kelly & Kim, 2007) or energy (Zio et al., 2012) networks. They analyze the impact of the loss of one edge (Jenelius et al., 2006), and sometimes propose indicators, like Network Trip Robustness (Sullivan et al., 2010), or Network Robustness Index, or k-edge survivability index (Myung & Kim, 2004), to characterize the capacity of the network to resist to the disruption (Chen et al., 2002). We analyze here the sensitivity of removing edges to the occurrence of nodes knowing interdependencies between them.

### 3.3.3 The two tests in other contexts

Simplification of the network is performed here by removing the weak edges. It is a desired, albeit fictitious event, which is the suppression of one edge. This corresponds to network reduction ambition, to reduce calculation time (or prevent it to diverge to infinite) and increase human capacity to visualize and understand network behavior.

The general question is: “Under what circumstances and conditions is it worthy to simplify network by removing weakest links?” This implies several sub-questions: 1/ What is the definition of weak link, and is it absolute or relative? 2/ What does “worthy” mean, or what is an acceptable loss of precision in the network analysis? 3/ How to characterize networks to know a priori if simplification under these conditions is reasonable or not?

Two tests on real past modeled networks are made to illustrate this research. We are then in the first and second step of a classical Design Research Methodology (Blessing and Chakrabarti 2009; Laurel 2003), formalizing questions from descriptive studies, and proposing and testing a new concept on these past case studies. We are not at the prescriptive study step yet, with an ongoing analysis where decision-makers are present.

As mentioned in (Kilani & Marle, 2019a), it had been considered at the beginning of this Ph.D. to initiate a decision-decision network at Total Energies and to test its simplification. However, the actual evolution of this Ph.D. did not permit to run this analysis.

Two gaps were analyzed:

- the gap between the simplified network and the complete network,
- the gap between the simplified network and the initial list, since things were initially managed as lists, without considering interdependencies (or with very basic principles).

Details are in (Kilani & Marle, 2019a), but to wrap-up, in both cases the simplified network analysis is closer to the complete network analysis than the basic analysis without network consideration. This precision is still sensitive to the structure of the initial network and the position of weak links. Three conclusions had been drawn from this initial work.

Since we had discrete values with a lot of ex-aequo, it was easier to use absolute thresholds. However, decision-maker may want to remove a certain percentage of edges, whatever the absolute values. Another point was to assess the impact of location of these weak links in the network. Are these links buried with main blocks (or clusters) in a DSM or are they off diagonal (and outside the blocks)? Do these links represent feed forward or feedback information dependencies?

Among the acceptable loss of precision, this depends on decision-maker’s intention and on company policies. The two examples introduced here showed different practices with different perceptions of what is acceptable or not. In the first case, relative gaps and rankings were important. That could make a difference to be at the 10th or 11th place.

Another interesting point after these first two cases is that simplifying the network seems to keep its global structure, its “shape”, as shown in Figure 23. The Tramway network with a funnel shape kept a funnel shape, albeit some paths were smaller or even cut. The CEA network with a “spaghetti dish” shape kept this shape, albeit some nodes were put outside the new network.

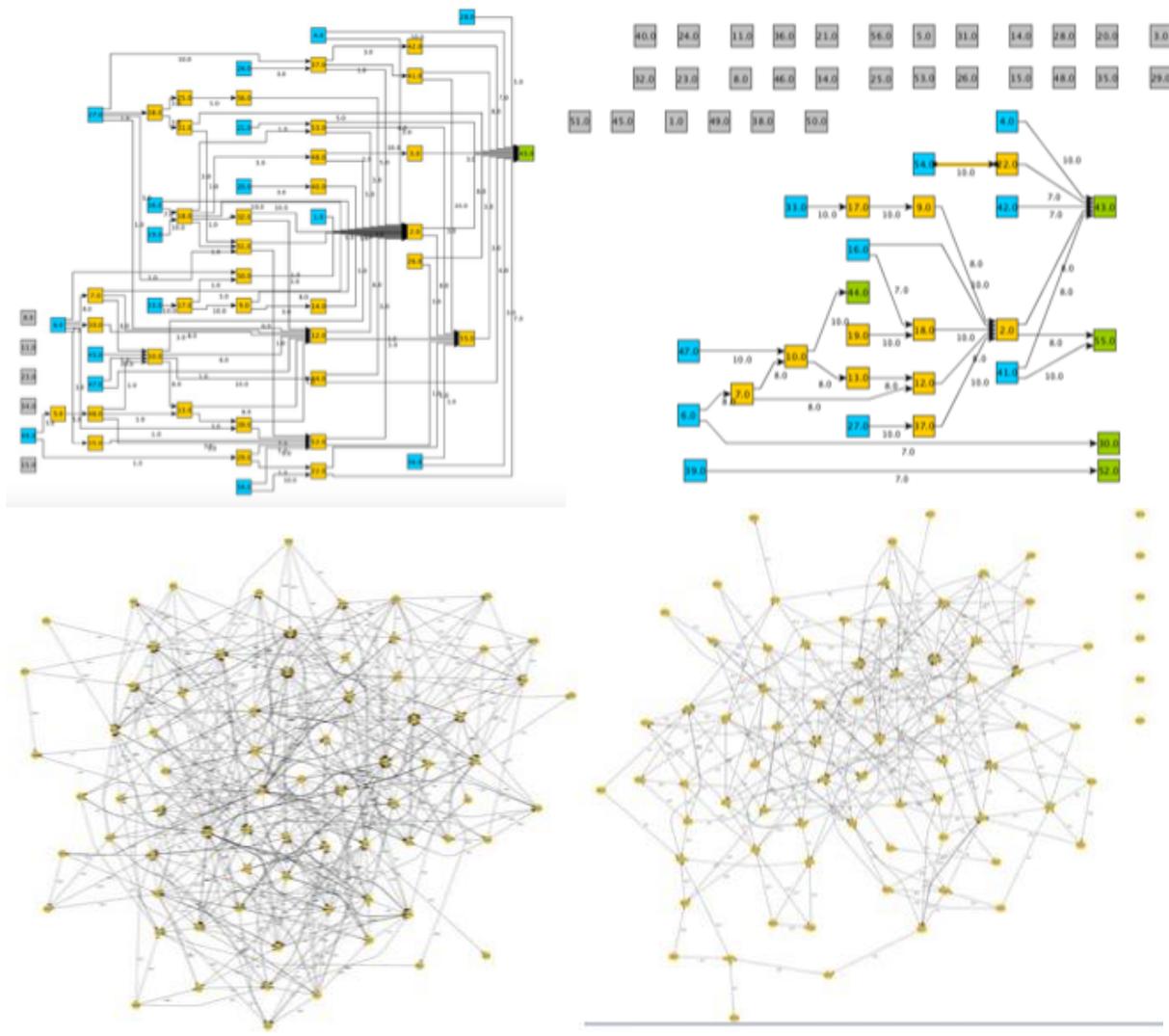


Figure 23: the Tramway (up) and CEA (down) networks, with complete (left) and simplified (right) versions

This is not a generic conclusion, but after 2 cases we noticed that a spaghetti seems to have very little chance to evolve to a funnel when keeping strong links only.

### 3.3.4 Intermediary conclusion about the possibility to apply network simplification in our context

The results show first that it is possible in some situations to make such a simplification, since the simplified network analysis is closer to the complete network analysis than the basic analysis, made without network consideration. Second, this precision is sensitive to the structure of the initial network and the position of weak links.

Even if previous works were in a different context (risk-risk network), we argue that this approach could be suitable for a decision-decision network. The main reason is the heterogeneous nature of both objects. Indeed, risk is a polymorphic concept, with risks associated to each dimension of the project, e.g., delay risks, over cost risks, legal risks, operational production risks, organizational risks.

With our decision network model, simplified or not, we have now to set the precise scope of the multi-decision problem. This is the object of the next paragraph.

### 3.4 Formulating the local multi-decision problem (making $P$ decisions among $N$ )

The main objective of this section is to help formulate the problem, notably by selecting which decisions to include within the scope of the problem as considering the whole decision network can be challenging. As a reminder, this means that from an initial network with  $M$  decisions, only  $N$  decisions are considered, to finally make  $P$  decisions. To do this, a related work on clustering methodologies is first presented. Then, two approaches are proposed, inspired by these related works, respectively the top-down and the bottom-up approach.

#### 3.4.1 Related work on clustering methodologies

Clustering consists in grouping the nodes of a graph into groups, called clusters, by considering the distribution of edges in that graph (Schaeffer, 2007). This ensures that the connection is dense enough within each group and weaker between groups. Graph clustering is also considered as a sort of classification applied to a finite set of objects (Jain & Dubes, 1988).

In practical terms, graph clustering has been used to organize and group raw data into homogeneous groups so that the data items assigned to a given group share similar characteristics or have strong interactions (Ventroux, 2015). It is based on an algorithm allowing to obtain clusters and validate them to check initial parameters satisfaction (Jaber, 2016).

Different measures are possible to identify good clusters. There are measures based on vertex similarity criteria, distance function, and cluster fitness measures (Marle & Vidal, 2011b). The assumption of the first measure is that the higher the similarity of the vertices, the more they need to be grouped in a single cluster. On the opposite, with distance measures, it is desirable to group vertices having small distances from each other. This can be done by, for example, using the Euclidean distance. As for the cluster fitness measures, they allow to evaluate the relevance of potential clustering solutions by determining those that satisfy a certain condition defined by the decision maker, such as the number of targeted clusters and the maximum number of elements in each cluster. More details about these measures are provided in the following works (Donetti & Muñoz, 2008; Marle & Vidal, 2011b; Schaeffer, 2007).

Graph clustering has been of great interest for a long time, leading to the development of various algorithms (Newman, 2004). The following paragraphs discuss two ways for building clusters, respectively flat and hierarchical clustering.

### 3.4.1.1 Partitioning methods: Flat clustering

Flat clustering is based on a single partition. It creates a flat set of clusters without providing an explicit structure to connect these clusters together. It has been developed in different contexts, forming clusters of different objects such as activities, actors, complexity-induced project failure factors (Montequín et al., 2018), deliverables (Jaber et al., 2018), product components (Es, 2012), project scheduling problem-related behaviors, project actors (Jaber, Marle, and Jankovic 2015), project risks (Marle et al., 2013; Marle & Vidal, 2011a), and project decisions (Campagna et al., 2020) (Rudeli, Viles, and Santilli, 2018).

To provide a concrete idea of what this method is, an illustrative example is presented in Figure 24. We have a graph with N nodes. By applying a flat clustering, four clusters are constructed.

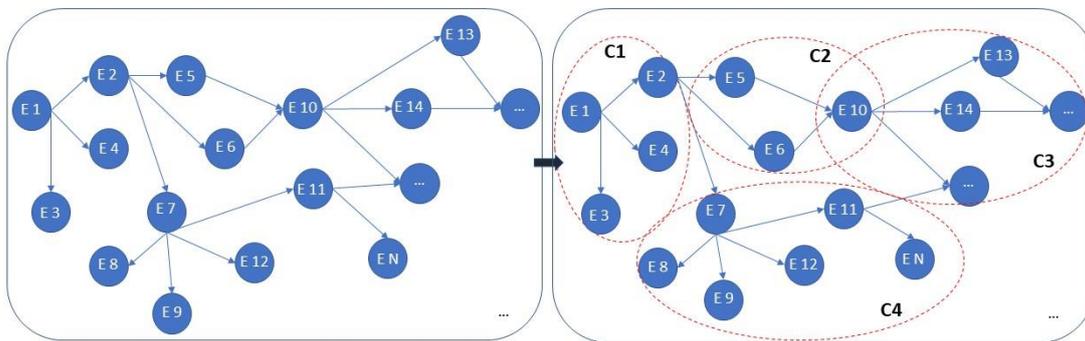


Figure 24: An example of flat clustering

This type of clustering has been performed based on different parameters. For instance, (Fang et al., 2010) developed an algorithm to cluster risks based on their interactions. Ventroux and co-authors proposed to group actors by focusing on the most vulnerable interactions, which allowed to group actors from different internal and/or external entities that are involved in complex phenomena (Ventroux et al., 2017). Es proposed an algorithm that constructs clusters containing elements with a high degree of connectivity and prevents these elements from being assigned to multiple clusters, as this can be confusing (Es, 2012).

This type of clustering offers several advantages in decision-making and management. For instance, building groups of stakeholders engaged in numerous collaborative decisions can lead to coordinated and potentially more collective decisions (Ventroux et al., 2017). Risk clustering can improve the effectiveness of risk management of a project and improve coordination between stakeholders involved in the management of this project (Marle & Vidal, 2014). In the field of product architecture modularity, components clustering can reduce the coordination complexity in a product development project (Es, 2012).

### 3.4.1.2 Hierarchical Clustering

Hierarchical clustering is characterized by a hierarchical structure which allows to create a hierarchy of clusters. In other words, in such a structure, each top-level cluster is composed of sub-clusters, and so on. As can be seen in Figure 25, this allows to produce multi-level clusters which takes the form of a tree, known as a dendrogram. This dendrogram provides an overview of the number of clusters existing in the set of objects (Amine et al., 2008).

The tree shown in that figure groups 23 elements into clusters at four intermediate levels. Each level, indicated by dotted lines in the image, can be interpreted as a possible clustering solution. This means that there is no single solution (division) but even the decomposition level is in itself a choice (Schaeffer, 2007).

To obtain a possible clustering solution, a cross section of the tree can be made at any level. The intersection of the dotted line with the branches of the tree gives the number of possible clusters. The elements of each cluster are those that remain in the same branch of the dendrogram tree above the line. For example, for the first level I, four clusters are possible. The first one includes elements from 1 to 8, the second one from 9 to 14, the third one from 15 to 17 and the last one from 18 to 23. Several cuts can be made, each of them leading to a new division with smaller clusters. The decision-maker is not necessarily concerned by the complete hierarchy but by a single level (division), obtained by cutting the tree by a horizontal line (Amine et al., 2008).

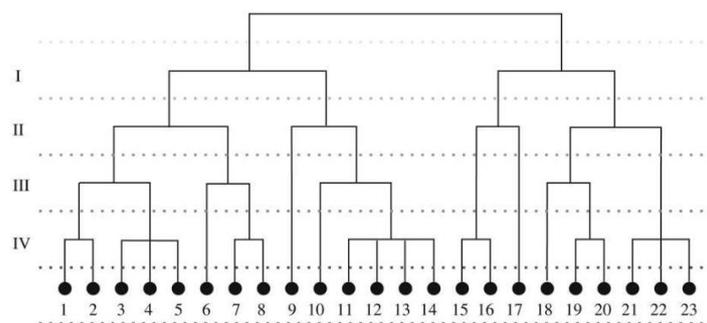


Figure 25: An example of a dendrogram composed of 23 elements, source (Schaeffer, 2007).

However, this method does not provide any information to the decision-maker regarding the best level of cut. It is up to the decision maker to make this choice and decide the number of clusters he or she would prefer (Amine et al., 2008; Newman, 2004). This choice really depends on what the decision maker is looking for. In fact, asking how many clusters are involved in a given dataset is equivalent to asking at what granularity the decision maker is supposed to examine at his data.

There are two ways to build hierarchical clustering (Jain & Dubes, 1988; Marle & Vidal, 2011b; Schaeffer, 2007). The first one is called “Descending Hierarchical Clustering” or “Top-Down / divisive algorithms”. The second one is called “Ascending Hierarchical Clustering” or “Bottom-up / agglomerative algorithms”. These two algorithms are exactly the opposite of each other and are presented in the following paragraphs.

### 3.4.1.2.1 Top-Down or divisive algorithms / Descending Hierarchical Clustering

The concept of Top-Down or divisive algorithms starts with a graph or a group of elements (M) and decomposed it into a set of diverse sub-groups (clusters) according to predefined criteria (constraints and objectives). Then, each sub-group is recursively partitioned. To provide a concrete idea of what this method is, an illustrative example is presented in the following Figure 26. This figure must be read from right to left.

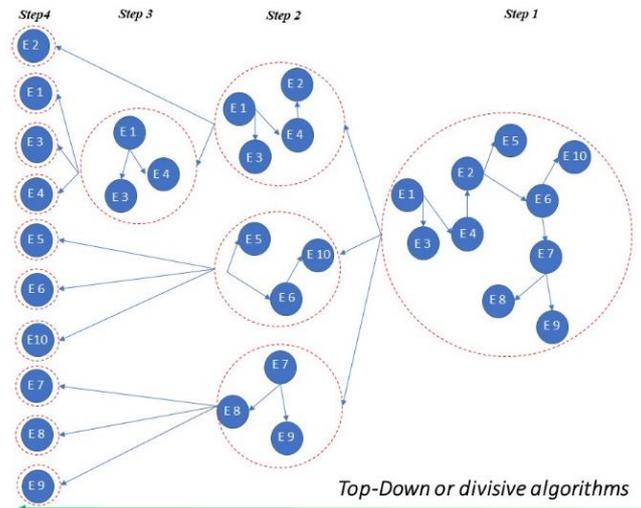


Figure 26: An example of Top-Down or divisive algorithms ( $M=10$ )

### 3.4.1.2.2 Bottom-up or agglomerative algorithms / Ascending Hierarchical Clustering

Beyond breaking the graph or a set of elements down into clusters, it is also possible to merge singular elements iteratively into clusters (Schaeffer, 2007). For this method, it first places each singleton element in a cluster by itself. At each iteration, the most similar or closed clusters (singletons or larger) are combined in the same class to provide a larger cluster (Amine et al., 2008; Donetti & Muñoz, 2008; Hopcroft et al., 2003).

Individual elements are thus grouped into pairs, and then the pairs start to be connected to other pairs or to other individual elements. This process is repeated until a certain final condition is met or the expected number of clusters is achieved (Schaeffer, 2007). This process eventually results in clusters of elements. Merging elements into a cluster can also be performed using various measures, as discussed previously in section 3.4.1.

The next figure 27 shows an example of such method. The nodes at the left of the figure marked here by E1, E2, E3, E4,..., and E10 represent the individual nodes (singletons) at the beginning of this process, while the groups of nodes at the top represent the clusters after all singletons have been processed and combined into clusters (Newman, 2004).

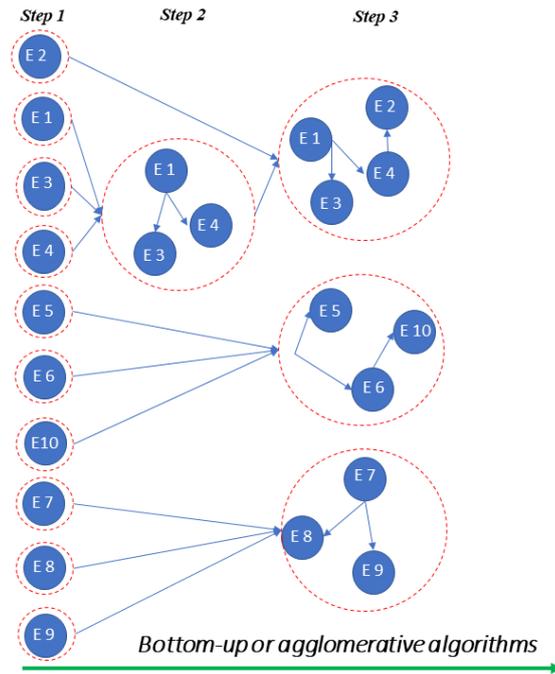


Figure 27: An example of Bottom-up or agglomerative algorithms ( $M=10$ )

However, this method has some limitations. Hopcroft and co-authors mentioned that it tends to be sensitive to changes that occur in the input data and showed that the level of instability in their case study was dramatic (Hopcroft et al., 2003). In addition, the calculation time can be long if we have a high number of elements to analyze.

After this presentation of existing literature, we are now going to introduce two approaches for our problem. They correspond respectively to a top-down (or descending) and a bottom-up (or ascending) approach. They use two parameters: interdependency between decisions and their temporality. The temporality parameter reflects the date of the decision to be made. As mentioned in Chapter 2, decision dates are used in the proposed decision-making process as inputs, but they have not been explored further. This will be detailed in Chapter 7.

### 3.4.2 The top-down approach

The top-down approach consists in choosing  $P$  decisions among  $N$  that will be outputs of the multi-decision-making process. It is made up of two steps based on the literature. Step 1 consists of building up packages of decisions among the total set of  $M$  decisions, using a clustering approach. Step 2 consists of identifying which decisions should be made simultaneously within each package. More details on these two steps are provided in the following.

#### *3.4.2.1 Step 1: Building up dense clusters of interdependent decisions to help determining the environment of $N$ decisions that will be considered during the coordination process*

Let  $M$  be the total number of decisions initially modeled in the project decision network.  $M$  can easily range from several tens to several hundred (each having several alternatives) in the context of complex projects, notably industrial mega-projects. It is thus challenging to consider the whole decision network at once, and it might be ineffective to consider separately one decision at a time since we may have compatibility issues and rework.

Two highly interdependent decisions,  $D_1$  and  $D_2$ , are likely to be studied simultaneously since the choice of an alternative for  $D_1$  is likely to impact the choice of an alternative for  $D_2$  strongly. This observation calls for identifying packages of highly interrelated decisions, which means that managers would be interested in possibly studying them together. In other words, Step 1 consists in building up clusters of decisions, depending on their interactions.

Many parameters and constraints can define clustering problems. In our case, clustering is performed according to the interaction level between decisions, which means that the clustering problem aims at maximizing the interactions between decisions within the formed clusters (Objective function).

We added the 3 following constraints to the problem formulation by discussing with decision-makers.

**Constraint C1.** In our study, industrial decision-makers preferred the clusters to be disjoint, meaning each decision can belong to one and only one cluster. This choice was preferred since, operationally, it permits to simplify the process. Indeed, if a decision  $D_i$  is present in two clusters or more, then the choice of an alternative for  $D_i$  should be made considering its presence in several clusters, which does not reduce the complexity of the decision process. However, the reader or future practitioners might prefer to replace this strict constraint with a constraint stating that a decision should not belong to more than  $C$  clusters, where  $C$  is an integer strictly superior to 1.

**Constraint C2.** A possible constraint to prevent the result of the clustering process from being a single cluster of  $M$  decisions (the amount of decision interactions being obviously maximal), is to limit the size of the clusters to  $N_c$ , where  $N_c$  is an integer between 2 and  $(M-1)$ . However, in the case of our study, practitioners considered it was challenging to determine  $N_c$  a priori, meaning C2 was not present in the formulation of our problem. C2 has been replaced by constraint C3.

**Constraint C3.** This last constraint is a density constraint, stating that the clusters should be at least  $\alpha$  times denser than  $\Delta$ , where  $\Delta$  is the initial density of the global set of  $M$  decisions. Decision-makers found this constraint more relevant since it allows them to focus on forming clusters of highly interrelated decisions. Moreover, at equal density, it is preferred to have a distributed rather than concentrated density. Let us for instance consider two clusters of three decisions,  $C_1$  and  $C_2$ , with the same global level of decision interactions (6).  $C_2$  will be preferred to  $C_1$  if all  $C_2$  decisions are connected (with a level of 2) and if in  $C_1$ , the first and second decisions are independent and only related to the third one (with a level of 3). The decision-makers can define  $\alpha$  a priori based on their former experience or conduct several clustering processes using several values of  $\alpha$ . They thus choose the best result in the end, or they may perform a complementary frequency analysis of the results (Marle & Vidal, 2011b).

At the end of this step, the initial set of  $M$  decisions has been split into clusters of different sizes. The question now is to identify the decisions that must be made simultaneously within each cluster.

#### *3.4.2.2 Step 2: Choosing the $P$ decisions among $N$ that will be outputs of the multi-decision-making process (Top-down)*

Let us consider one decision cluster composed of  $N$  decisions. Step 2 aims to identify decisions within this cluster that should be taken simultaneously. We already know that the decisions within the cluster are likely to be highly interrelated since a minimal level of cluster density has been added as a constraint in Step 1.

When decisions are too distant in terms of time, making them simultaneously might thus be risky. Indeed, we have a low guarantee that all decision alternatives are clearly defined, and even if they are clear, they may be insufficiently stable (Graves and Ringuest, 2009), (Moura, 2012), (Cinelli et al., 2021). In other words, it is possible to face situations under which the conceptual alternatives are known while the project alternatives are still undetermined as these decisions are distant in time (Van Der Kleij, Hulscher, and Louters, 2003). On the contrary, decisions are likely to be simultaneously made when enough stable information is known about them since they belong to the same timescale (Figueiredo and Souza, 2012).

Consequently, Step 2 proposes to perform a temporal clustering based on the date  $T_i$  at which each decision  $D_i$  is supposed to be made ( $T_i$  is a parameter associated with each decision). For each cluster, a graph is drawn, as shown in Figure 28, to represent the distribution of dates  $T_i$  on a time scale, which can help constitute the packages visually. Moreover, the calculation of inter-decile distances can help the decision-makers to identify the temporally close decisions through the ranking of inter-decile distances in ascending order (the smaller the distance, the more relevant it is to make the decisions simultaneously) (Denzil G. Fiebig, 2018).

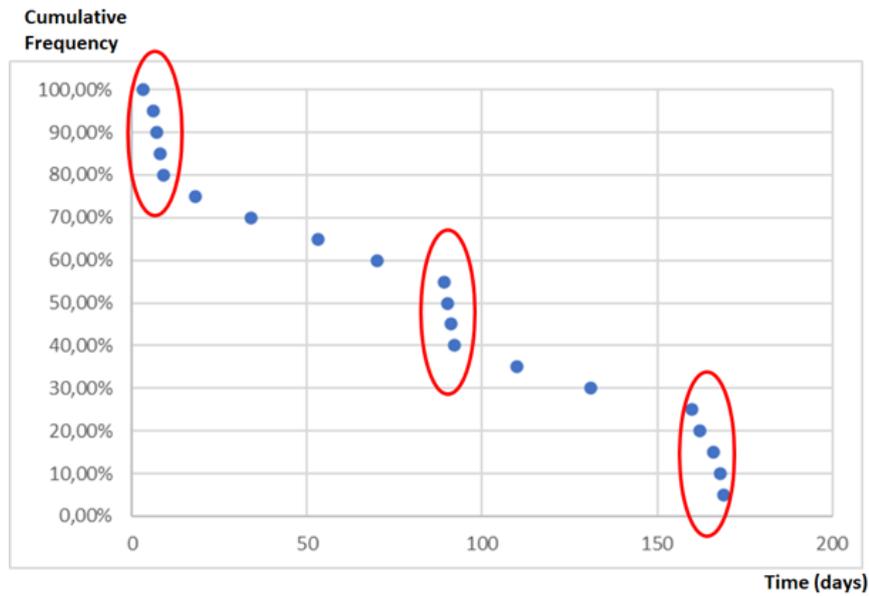


Figure 28: Distribution of the decision dates within the cluster and identification of packages

Two cases can be identified from this graph. On the one hand, if all the decisions in the cluster are temporally close, then the entire package is processed at once, and decisions are made simultaneously, with a focus on their interdependences: this is a complete “synchronous strategy” (***N among N***).

On the other hand, if all the decisions in the cluster are temporally distant, each decision is made one at a time, one after the other. Each decision is made considering its interactions with previous decisions and its interdependencies with the future decisions to be made this is a complete “asynchronous strategy” (***I among N***).

The general case, shown in Figure 29, is a mixture of synchronous and asynchronous strategies in the same package (***P among N***), with several decisions to be made simultaneously and several decisions to be made alone. Thus, decisions that are temporally close are made simultaneously, and those that are temporally distant are made individually sequentially.

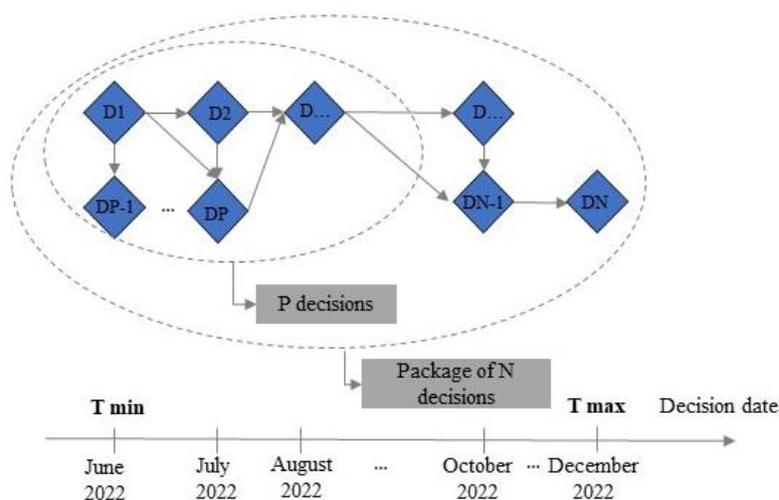


Figure 29: General Case: a mix of synchronous and asynchronous strategies

### 3.4.3 The bottom-up approach

The bottom-up approach also consists in choosing  $P$  decisions among  $N$  that will be outputs of the multi-decision-making process but starting from one single decision  $D_1$ . This decision is initially the only one that decision-makers are certain to consider. It is made up of two steps based on the literature. Step 1 consists of identifying the  $N-1$  decisions in the environment of  $D_{i_0}$  by studying the environment of  $D_{i_0}$  on a two-axis diagram. Step 2 consists of identifying the  $P$  decisions which should be made simultaneously (including  $D_{i_0}$ ) by defining conditions (thresholds). More details on these two steps are provided in the following.

#### 3.4.3.1 Step 1: Determining the environment of $N-1$ decisions that will be considered during the coordination process (Bottom-up)

Let  $D_{i_0}$  be the decision that the decision-makers want to focus on (or start with). At the time of the study, the decision-makers indeed want to consider  $D_{i_0}$  as an input to the problem. Instead of just making the  $D_{i_0}$  decision alone, they consider that it is related to other decisions, and thus want to study its environment. If  $D_j$  is another decision, then  $D_j$  and  $D_{i_0}$  can be related to one another according to two parameters:

- $I(i_0,j)$  : the overall level of interaction between  $D_{i_0}$  and  $D_j$  (that is to say from  $D_{i_0}$  to  $D_j$  AND from  $D_j$  to  $D_{i_0}$ ).  $I(i_0,j)$  varies from  $I_{i_0\text{-min}}$  to  $I_{i_0\text{-max}}$ , which correspond to the minimal / maximal overall of interaction when studying the relationship between  $D_{i_0}$  and all the other decisions in the project.  $I_{i_0\text{-min}}$  should be strictly superior to 0, so that if a decision  $D_k$  is not related to  $D_{i_0}$ , it should not be considered in this study focusing on  $D_{i_0}$ .
- $T(i_0,j)$  : the time between the dates  $T_{i_0}$  and  $T_j$  when the decisions  $D_{i_0}$  and  $D_j$  are supposed to be made, which means that  $T(i_0,j) = T_j - T_{i_0}$ .  $T(i_0,j)$  can be either positive or negative (depending on if  $D_j$  is supposed to be made before or after  $D_{i_0}$ ). However we assume that we do not consider the decisions that are supposed to have already been made, which means that  $T(i_0,j)$  should be superior to  $\Delta = (T - T_{i_0})$ , with  $T$  being the time when the study is conducted, and  $\Delta$  therefore being a negative value.

The total number of decisions that are identified under these constraints is defined as  $N$ . It presents the overall ensemble of decisions that should be considered, knowing that  $D_{i_0}$  is the initial decision the decision-makers want to consider. A two-axis diagram can therefore be built to describe the complete environment of  $D_{i_0}$ .

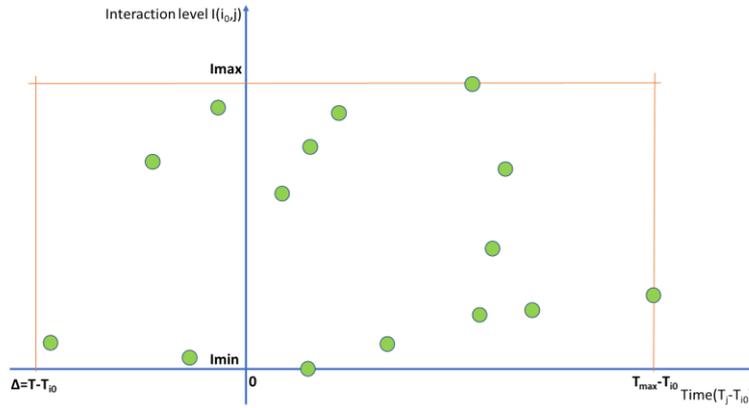


Figure 30: Bottom-up identification of the environment of a single decision  $D_{i0}$  on a two-axis diagram

It should be noted that the initial proposal here in the bottom-up approach is to define  $I(i_0, j)$  as the sum of the direct interaction from  $D_{i0}$  to  $D_j$  and from  $D_j$  to  $D_{i0}$ , meaning we only consider direct interactions between  $D_{i0}$  and the other decisions. A direct extension of this bottom-up approach consists in incorporating indirect interactions in the calculation of the  $I(i_0, j)$  by considering all the decisions that are linked to  $D_{i0}$  according to a path of successive interactions as long as this path is under a certain length. For instance, if we assume that, in terms of chain reactions we want to consider, we only focus on paths that have a maximum length of 2, then we would define  $I(i_0, j)$  by the following calculation :

$$I(i_0, j) = (I_{i_0 \rightarrow j} + I_{j \rightarrow i_0}) + \sum_{\substack{D_k \text{ when the interaction path} \\ D_{i_0} \rightarrow D_k \rightarrow D_j \text{ AND/OR } D_j \rightarrow D_k \rightarrow D_{i_0} \text{ exist}}} ((I_{i_0 \rightarrow k} + I_{k \rightarrow j}) + (I_{j \rightarrow k} + I_{k \rightarrow i_0}))$$

### 3.4.3.2 Step 2: Defining thresholds to identify the $P$ decisions to be made together, including $D_{i0}$

The two-axis diagram being built, and the  $N-1$  decisions environment thus being identified, similarly to the top-down approach, the distributions of decisions can be described on each of the axis. Two thresholds can therefore be defined:

- $I_{i0}$ , which is the threshold of the interaction axis: it means that  $X\%$  of the  $N$  decisions verify the condition  $[I(i_0, j) \geq I_{i0}]$ . The proportion  $X$  is left to the choice of users, even though the calculation of inter-decile distances can help the decision-makers better choose the value of  $Y$  given the nature of the dispersion of the  $I(i_0, j)$  values.
- $\partial_{i0}$ , which is the threshold of the temporal axis: it means that  $Y\%$  of the  $N$  decisions verify the condition  $[-\partial_{i0} \leq T(i_0, j) \leq +\partial_{i0}]$ , meaning that in absolute value, decision  $D_j$  is not distant from  $D_{i0}$  by a time superior to the value  $\partial_{i0}$ . The proportion  $Y$  is left to the choice of users, even though the calculation of inter-decile distances can once again help the decision-makers better choose the value of  $Y$  given the nature of the dispersion of the  $T(i_0, j)$  values.

As a whole, the set of P decisions which should be considered can be defined as  $D_{i0}$  plus the (P-1) decisions that respect the two following conditions in terms of thresholds:  $[I(i_{0,j}) \geq I_{i0}]$  and  $[abs(T(i_{0,j})) \leq \partial_{i0}]$ . Visually, this corresponds to the following diagram.

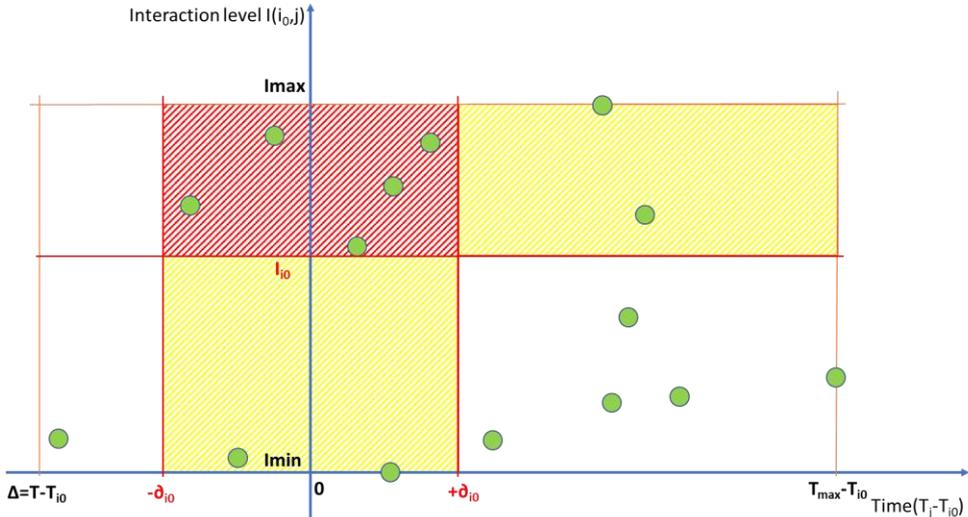


Figure 31: Identification of the (P-1) decisions to be made together with  $D_{i0}$  (Red-striped area)

It should be noted here that these thresholds rules have been discussed with industrial practitioners as rules that could be easily put in place for all practical purposes. Still, they have the drawback to exclude decisions which have a bad evaluation on one of the two axes even though they would have a good evaluation on the other axis (for instance, a decision  $D_j$  can be excluded if it is too distant in time even if it is very interrelated to  $D_{i0}$ ). Future rules might therefore be defined to add additional decisions in the set of decisions to be made together to include part of the decisions in the yellow-striped areas on Figure 31 (the yellow-striped areas corresponding to the decisions which respect one of the two threshold rules only).

### 3.4.4 Intermediary conclusion about the methodological choice associated with scope delimitation

As presented in the two previous paragraphs, two approaches are possible to delimit the scope of the decision problem.

The advantage of using the Top-Down approach is that it is widely known and applied in the context of project management as a tool to manage different types of objects. Thus, in terms of application, it is likely that some decision-makers will feel more confident in choosing this approach over the bottom-up approach.

The advantage of the bottom-up approach is that it has specifically be tailored in this work to this context and could better account for the actual distribution of decisions in the network (number and weight of interactions).

Both approaches present practical limitations. With the Top-down approach, decision-makers might find it difficult to determine the constraints of the clustering problem (in particular, density or size constraints). Similarly, the Bottom-up approach requires defining initial thresholds and the initial decision  $D_{i0}$ . Each approach having its own advantages and disadvantages, it is up to the decision-makers to choose the one that suit best his context.

However, regardless of the choice made, both approaches allow to delimit the scope of the problem by proposing one general coordination strategy with two other strategies derived from it. The general one consists in making simultaneously  $P$  decisions among  $N$ . This strategy is a mixture of synchronous and asynchronous strategies applied to the same package, with several decisions to be made simultaneously and several decisions to be made separately.

For the two other strategies, the first one consists in making one decision among  $N$  considering its interactions with previous decisions and its interdependencies with the future decisions to be made; this corresponds to a complete "asynchronous strategy" (1 among  $N$ , with  $P=1$ ). This case is applicable if all the decisions in the cluster are temporally distant. In other words, each decision is made one at a time, one after the other.

The second extreme strategy consists in making  $N$  decisions among  $N$ . This case is applicable if all the decisions in the cluster are temporally close. In other words, the entire package is processed at once, and decisions are made simultaneously, with a focus on their interdependences: this is a complete "synchronous strategy" ( $N$  among  $N$ , with  $P=N$ ). The example developed in Chapter 6 will illustrate this strategy.

All the three strategies allow to better coordinate multiple decisions and ensure consistency of highly interdependent ones. They can be performed with or without clustering. Clustering is here to provide an assistance, but the principle of selecting  $P$  decisions to make from a package of  $N$  interdependent decisions is still interesting without advanced clustering techniques.

### 3.5 Chapter conclusion: how to properly formulate the multi-decision problem

Throughout this chapter, the first step of the proposed decision-making process has been presented, based on a decision network modeling.

Graphs and matrices have first been presented as possible techniques to model the decision network. In addition, the issue of simplifying the decision-making network was discussed as a potential solution to deal with the complexity of the network. This technique consists here in removing the weak edges between the nodes of decisions. In this Ph.D. thesis, we did not have the opportunity to test this technique on a real decision network, but it would be interesting to do so on further work.

Then, two possible approaches are discussed for defining the scope of the problem. These approaches consider two parameters, namely the interdependency strength and the temporality gap between decisions. In practice, decision groups are constructed so that the rate of interaction of decisions is maximal inside the groups but minimal outside, and decisions are temporarily close to each other. This led to a synchronous coordination strategy, an asynchronous coordination strategy or a mixture of both.

The main objective of the first step is to formulate properly the multi-decision problem to contribute to facilitating the coordination of multiple decisions that are highly interdependent. Thus, we argue that the ability of decision-makers to make coordinated decisions and the consistency of highly interdependent decisions will be enhanced if the decision problem is formulated following one of the two proposed approaches.

To summarize, our first proposal so far is to model the decision network and then to delimit the scope of the multi-decision problem using the appropriate approaches. At this stage, model inputs are decisions  $\{D_1, D_2, D_3, D_4, \dots, D_i, \dots, D_M\}$  characterized by the dates at which they should be made  $\{T_1, T_2, T_3, T_4, \dots, T_i, \dots, T_M\}$ , where  $i \in \{1 \dots M\}$  and their interdependencies  $I_{ik}$ , where  $i$  and  $k \in \{1 \dots M\}$ .

Chapter 3 outputs are respectively a vector of  $N$  decisions considered as strongly connected and temporally close, and a vector of  $P$  ( $1 \leq P \leq N$ ) decisions that have to be taken. This vector will be the final decision process output.

The next chapter will introduce another input which is the alternatives of decisions  $D_{i,j(i)}$  and the output of the model, which is a decision scenario.

4 Chapter 4: Structuring the problem to propose relevant and plausible scenarios assembled from decisions alternatives

This Chapter introduces the notion of scenario that will be used to describe the assembly of an alternative for each decision. This is only for the  $P$  decisions that are to be made, not the  $N-P$  decisions that are considered in the environment of the latter. Three strategies are proposed to generate scenarios that combine compatibility and performance.

#### 4.1 Introduction: the use of scenarios to add the notion of compatibility between decision alternatives

The term scenario is commonly defined as a sequence of planned or imagined events. Norouzi and his co-authors cited in their work the definition proposed by Mohtadi (1996), according to which "a scenario is a description of the future and pictures of the paths that take us to the probable future" (Mohtadi, 1996; Norouzi et al., 2020). Scenario planning is considered a management tool that can be used to improve the quality of decision making and contribute to more effective and resilient strategic decisions (Wilson, 2000). It is "a systematic, participatory (in most cases), judgmental, and prospective process aimed at developing plausible narratives of future events" (Hafezi et al., 2017).

This tool has been used in many fields such as project management and energy sector. For instance, in the context of project management, the concepts of risk scenario, treatment scenario, and project scenario have been used to characterize and evaluate project alternatives (Marmier et al., 2013). In that context, a risk scenario describes the combination of risks that occur during a particular variant of the project. Ventroux has also used this concept to generate contract strategy scenarios (Ventroux, 2015). A scenario in that context is defined by the relationship between a cause, a target, a consequence, and their interactions (Ventroux, 2015). In the energy sector, it has been used to project plausible scenarios for the Iranian oil and gas industries (Hafezi et al., 2017).

According to Spaniol and Rowland (2018), scenarios must meet three conditions. The first is that they must be possible, the second is that they must be internally plausible and not self-contradictory, and the third is that they must take the form of a story or narrative description (Spaniol & Rowland, 2018). The plausibility condition is important, especially in our context since decisions are interdependent, and so are their alternatives. Ensuring that the scenarios are plausible implies ensuring the compatibility between the different decision options. The development of a plausible scenario helps to avoid indirect negative impacts and achieve the planned objectives. The scenarios must also be objective, and their selection must not be biased. If these requirements are not met, the resulting scenarios will be unreliable.

In this Ph.D. thesis, we therefore define a scenario as follows:

**Definition:**

A scenario is composed of an assembly of decisions alternatives that are defined according to plausibility and relevance criteria. A single alternative  $D_{ij}$  is selected per decision  $D_i$ .

The scenario plausibility is related to the compatibility between the different decision options. The scenario relevance is related to the performance of decision alternatives regarding project objectives.

A decision scenario is, thus, designated by  $\{D_{1,j(1)}, D_{2,j(2)}, D_{3,j(3)}, D_{4,j(4)}, \dots, D_{i,j(i)}, \dots, D_{p,j(p)}\}$ , with  $P$  the total number of decisions and  $j(i)$  the  $j^{\text{th}}$  alternative of decision  $i$  ( $j$  is not fixed, it is dependent of decision index  $i$ )

To generate scenarios, three additional types of information are thus needed:

- Decisions x Decision Alternatives (D-DA) for identifying and structuring possible alternatives for each decision (this may be called a DMM for Domain Mapping Matrix, or a heterogeneous graph).
- Decision Alternatives x Decision Alternatives (DA-DA) for identifying and assessing the compatibility degree between each couple of decision alternatives (like a DSM or Design Structure Matrix or a homogeneous graph).
- Decision Alternatives x Project Objectives (DA-PO) for identifying the performance of decision alternatives (another DMM or heterogeneous graph).

We present in following sections three possible strategies that will use these data (plus D-D).

The first one relies on the sequential consideration of scenario plausibility then relevance. It is related to a classical matrix-based approach called morphological approach. Data is structured with matrices, and algorithms can be used to explore and select a first set of plausible scenarios. Then, a second algorithm can be run for a second selection considering relevance.

The second one considers simultaneously plausibility and relevance. This means that with the same data, scenarios are generated considering both parameters. This may be more challenging and imply more often the use of a computer-based assistance. The QFD approach is the most known and adequate method for applying this strategy, still with a matrix-based format.

The third one is voluntarily based on manual exploration of feasible spaces, considering alternatively or simultaneously compatibility and performance of decisions alternatives. It is less dedicated to find an optimal solution, but more relevant to find solutions during a meeting (pre-validation committee) with the actors involved in the decision process. It is based on heuristics rather than computer-based algorithms. Moreover, it is often more suitable to explore progressively scenarios using the graph format.

A fourth one, quite classical, would have been to consider relevance, then checking plausibility. However, it may involve dead ends, or iterations, or reluctance to iterate since we found a very high-performance scenario. The problem is if this scenario is composed of very incompatible alternatives. To fight this natural tendency to prioritize performance over compatibility, we never propose this strategy.

## 4.2 Building plausible then relevant scenarios (with a matrix-based approach)

This section introduces a 2-step scenario generation process, where scenarios are screened out for plausibility first then relevance. This corresponds to the morphological approach.

### 4.2.1 Description of the morphological approach

The morphological analysis or the general morphological approach (GMA) is a conceptual modeling method, initially developed by Zwicky, the Swiss American astrophysicist and aerospace scientist, at the California Institute of Technology in the 1930s (Ritchey, 1998). The general definition of the term morphology refers both to the study of the structure and arrangement of the elements of an object, and to the way they combine to create a whole.

The objects that can be modeled are physical, such as an engineering system, social, such as an organizational structure, or mental, such as concepts of ideas (Ritchey, 2011). Clearly, this method is a popular method for structuring complex multidimensional problems and then exploring the possible scenarios or mapping future projections.

It has been applied in many domains such as engineering (Bardenhagen et al., 2022) and product design, security, safety, and defense studies (Johansen, 2018), creativity, innovation (Rakov, 2020), and knowledge management (Im & Cho, 2013), project management (Elmsalmi et al., 2021), energy (Arens et al., 2020), and many others (Hoolohan et al., 2019; Pereverza et al., 2017). For more details, we reference the work of Álvarez and Ritchey (2015).

However, only a few articles have applied this approach in the field of oil and gas industry. These include the work of Hafezi and co-authors, who have applied this approach in the Iranian oil and gas industries to generate a plan of plausible future energy strategies (Hafezi et al., 2017). Another work has used this approach to select the future oil production scenario (Alipour et al., 2017).

Furthermore, this method, according to Rakov, can be an effective analysis tool for conceptual and preliminary design, design development and decision making (Rakov, 2020). Indeed, morphological analysis has recently been used in the field of risk management to help managers improve their decision making. This is achieved by developing and evaluating risk mitigation scenarios from a list of initially identified risks (Elmsalmi et al., 2021).

General morphological analysis is based on two pillars of a scientific approach, which are analysis and synthesis. The analysis pillar is decomposed in three steps, which allows to build a morphological field to model the space of possible solutions while avoiding focusing on a limited set of solutions predefined in advance (Ritchey, 2006). The first step consists of identifying the most relevant criteria or parameters to describe the problem to be studied. These criteria, also known as plausibility criteria, are necessary for describing and evaluating the scenarios or the solutions to the considered problem (Duczynski, 2004). The second step identifies a spectrum of values or conditions for each criterion or parameter.

Once this identification is made, a morphological field can be constructed, and an n-dimensional configuration space can be created (Ritchey, 2012, 2015). For this purpose, a morphological matrix, also known as Zwicky box, is constructed with parameters in columns and their conditions in rows (Ritchey, 2002). A possible scenario is identified by selecting a single value for each parameter (Ritchey, 2006).

The main objective of this third step is to examine all the configurations and extract a set of plausible scenarios. However, this is not an easy task, especially if the number of combinations is significant, as it would be challenging and time-consuming to examine all scenarios. In general, with a morphological field that contains between 7 and 9 parameters with 5 conditions for each, we can count tens of thousands of possible scenarios.

Thus, it should be noted that even a small morphological field can contain a significant number of possible solutions. To further illustrate this point, consider the following example, in which a field of 6 parameters with a specified number of conditions for each parameter, contains  $2 \times 3 \times 2 \times 3 \times 2 \times 4 = 288$  possible configurations. In the following Figure 32, the selected cells represent one configuration or scenario among the 288 possible configurations of the complex problem. For each parameter (decision), only one condition (alternative) is chosen.

Value Proposition	Customer	Resource	Partner	Channel	Revenue Model
Private mobile virtual smart office solution	Private enterprise user	Mobile virtual smart office solution development resources	Mobile cloud computing infrastructure maintenance partner	Public channel	Monthly fee
Public mobile virtual space	Public mobile virtual space user	Mobile cloud computing infrastructure	Public mobile virtual app developer	Private channel	Freemium
	Public mobile cloud app programmer		Public mobile virtual smart office solution developer		App sales
					Solution development fee

Figure 32: A morphological space with 6 parameters, source (Im & Cho, 2013)

The second synthesis phase aims to converge on a shortlist of the most plausible scenarios or configurations. This will allow to reduce the total set of possible configurations in the morphological matrix to a smaller, more manageable set of internally consistent combinations (Im & Cho, 2013). In this way, a preliminary solution space is generated without necessarily considering all configurations (Ritchey, 1998). That is done by identifying conflicting or incompatible internal relationships between the levels of conditions. Cross-Coherence Assessment (CCA) is performed to ensure this phase. All relationships in the morphological matrix are examined and pairwise compared (Ritchey, 2012, 2015). That allows for the synthesis of consistent and compatible configurations. For each pair of conditions, an assessment determines whether or to what extent the pair of conditions may represent a consistent relationship (Ritchey, 2012, 2015).

So, only consistent scenarios are retained, which means that scenarios that contain contradictory conditions are eliminated. Depending on the structure of the problem, the number of possible scenarios can be considerably reduced, by approximately 90% (Ritchey, 2011). This assessment can be based on a plausibility selection process with several possible methods, including the plausibility index method (Duczynski, 2004; Hafezi et al., 2017). It uses plausibility indices to evaluate pairs of alternatives consistent with each other.

Consequently, condition pairs that are not consistent will be eliminated (Im & Cho, 2013). At this phase of the process, given the multidimensional nature of the matrix, an interaction between the different actors is strongly recommended, especially since the knowledge of the subject is never complete.

To conclude, using this approach, scenarios are constructed by estimating the conditions' levels and interdependencies so that they are mutually compatible. That leads to a set of plausible scenarios, which must thus be compared in performance with an adequate multi-criteria method, as morphological analysis is not able to evaluate them.

#### 4.2.2 Advantages and limitations, notably the lack of application in our context

In the following, we will briefly discuss the advantages of this approach that have greatly contributed to its popularity in domains with significant uncertainties and where new ideas of development are desirable (Hoolohan et al., 2019).

It uses a matrix format that can easily be exploited for other manipulations. The morphological approach fosters an environment that encourages discussion and debate since the participants in the synthesis phase are obliged to assess the coherence of the different conditions. Hence, this makes it particularly well suited to solving complex problems, especially those involving actors from different fields of expertise (Ritchey, 2011).

Moreover, this method has proven its ability to facilitate collective or synchronous decision-making requiring a high level of interaction between decision-makers and to overcome the cognitive difficulties faced during scenario development and selection (Pereverza et al., 2017). Such cognitive problems include focusing on a few scenarios instead of identifying the entire solution space, unconsciously favoring one of them, and relucting to try innovative alternatives because they are not familiar or because conventional alternatives have been successfully deployed in previous projects (Elmsalmi et al., 2021).

According to Hoolohan and co-authors, this approach attempts to stimulate reflection by facilitating the collaborative exploration of new relationships and scenarios beyond those that are most common (Hoolohan et al., 2019). In addition, developing a set of plausible scenarios can help to explore all possible scenarios without bias or prejudice and avoid selecting common scenarios that may not be relevant to the new case study.

In line with the above, a major strength of the morphological approach is its ability to identify new opportunities while minimizing costs before proceeding to the design phase and reducing the time spent on engineering studies (Bardenhagen et al., 2022; Goel et al., 2019). In addition, as in any modeling method, the accuracy of the input data entered in the morphological matrix is important. However, it is worth mentioning that with this method, the identification of parameters or conditions that are not correctly filled in can be highlighted immediately since cross-matrix evaluations can only be performed when all data are well defined and approved by all group members (Ritchey, 2011). A further advantage is that the steps can be easily followed and controlled by the decision makers. Thus, problems related to the lack of transparency, traceability, and clarity in the scenario development and selection process will be solved (Johansen, 2018; Ritchey, 2012). However, like any other method, the morphological approach has its own limitations. In fact, its process can be demanding in terms of time and resources, particularly the assessment of consistency which requires significant collaborative teamwork and considerable time (Johansen, 2018).

Additionally, this method can be criticized for relying on subjective assessments (Elmsalmi et al., 2021). Another limitation is that the synthesis step, which aims to identify plausible scenarios, may appear to some as a potential source of confusion and error if this identification is intended to be done manually. Therefore, the application of this method may require a specific computer tool that can facilitate this task (Eriksson & Ritchey, 2002; Ritchey, 2011).

The literature review cited in this section reveals that no study, as far as we know, has applied the morphological approach to develop decision scenarios in oil and gas development projects, whereas according to Eriksson and co-authors, this method is quite adequate for complex problems requiring multi-domain expertise such as those in oil and gas development projects (Eriksson & Ritchey, 2002).

Indeed, this approach can be very valuable in our context since each host country has its own regulations and conditions. It is thus relevant to generate plausible scenarios specific to each country. For example, a development concept built in a given country cannot be systematically reproduced in another country because it may be incompatible with the expectations of local authorities, the competence of local entrepreneurs, the environmental conditions and many other reasons.

Therefore, we propose to generalize the concept of morphological research and to include not only the study of technical, organizational, and social problem complexes, but also the study of the relationships between project decisions. We suggest to structure and model the whole decision problem, considering decisions as parameters, their alternatives as conditions and a scenario as a set of decision alternatives.

We will thus find that the morphological matrix in Figure 32 corresponds to D-DA. The compatibility between elements that allow for plausibility assessment corresponds to DA-DA. Once plausible scenarios are filtered, the last information DA-PO allows for selecting scenarios alternatives considering performance (regarding contribution to project objectives). As discussed in the section 4.1, an algorithm can be used to explore and select a first set of plausible scenarios. Then, a second algorithm can be run for a second selection considering performance. An example of the scenario generation algorithm will be introduced in the following section.

The following section describes the second strategy, consisting in considering simultaneously and not sequentially, plausibility and relevance.

### 4.3 Building simultaneously plausible and relevant scenarios (with a matrix-based approach)

This section introduces a 1-step scenario generation process, where scenarios are screened out for plausibility and relevance. This corresponds to the QFD approach.

#### 4.3.1 Description of the QFD (Quality Function Deployment) approach

The Quality Function Deployment (QFD) approach was initially introduced to develop better quality products to maximize the satisfaction of customers' needs. It provides a guide to effectively define customer requirements and convert them into detailed technical specifications to produce new products that meet those requirements (Bevilacqua et al, 2006). It was developed in Japan in the late 1960s by Yoji Akao, when Japanese industries moved away from traditional product development based on imitation and copying toward product development based primarily on originality (Akao, 1997). It was first industrially demonstrated in 1972 at Mitsubishi Heavy Industries (Bolar et al., 2017).

The main objective of this approach is to develop a quality assurance method which ensures that customer satisfaction is integrated into the development of the product before manufacturing. The deployment of the quality function (QFD) makes it possible to link customer needs to technical specifications and, consequently, to transform them into target values to ensure that products satisfy customer demands. It is a tool that allows “the voice of the customer to be translated through the various phases of product planning, engineering, and manufacturing. Each translation systematically uses a matrix based on the HoQ (House of Quality) framework” (Celik et al., 2008).

Figure 33, this approach is a 4-phase process, with a specific matrix dedicated to each phase (Patro, Chandra Sekhar; Prasad, 2013): the first identifies the customer's requirements, also known as the Voice Of the Customer (VoC), then the second matrix translates them into engineering characteristics of the products or services, also known as the Voice of the Engineer (VOE), process specifications are developed in the third matrix, and production control requirements in the last matrix (Paska, 2015; Singgih et al., 2013).

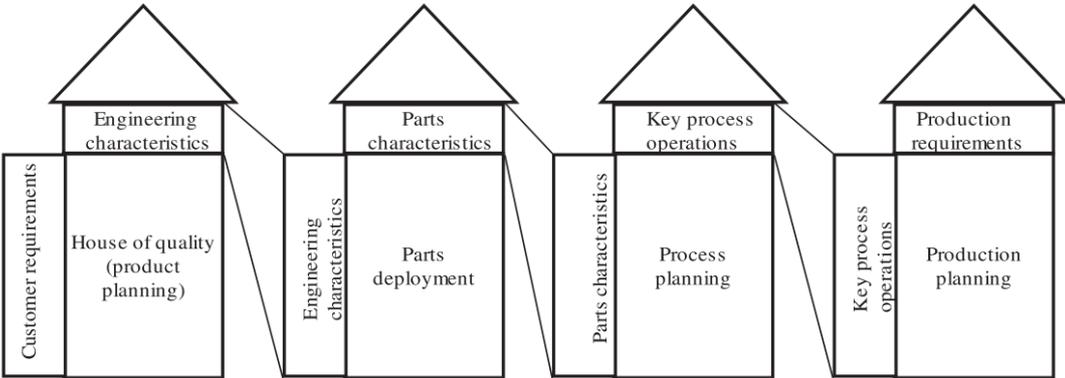


Figure 33: The four phases of QFD, source (Bossert, 2021)

The QFD uses a matrix called the House of Quality (HoQ) consisting of six parts which are illustrated in the following Figure 34 (Bergquist & Abeysekera, 1996):

- (1) Customer requirements which express the voice of the customers (the WHATs),
- (2) Planning matrix which usually contains the information regarding the priority of customer requirements
- (3) Technical characteristics which express the voice of engineers (the HOWs), corresponding to the customer requirements translated into measurable quantitative characteristics.
- (4) Relationship matrix which indicates the relationships between customer requirements and technical characteristics.
- (5) Correlation matrix which presents the interdependencies between various technical characteristics. The strength of the interactions between the alternatives is noted in the "roof" of the QFD.
- (6) Technical characteristic importance rankings.

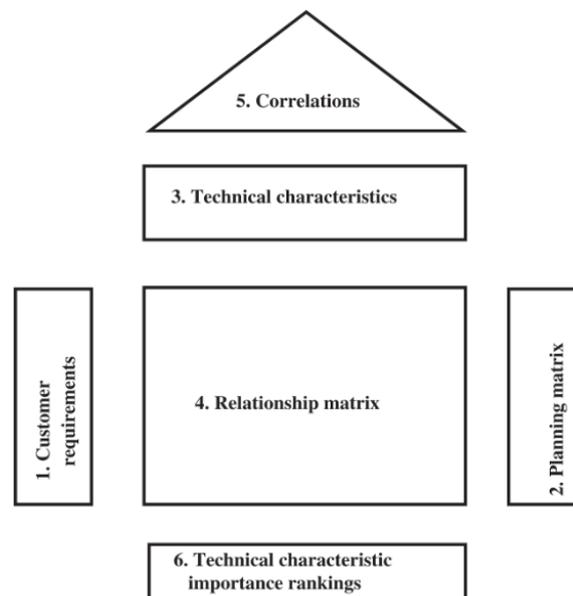


Figure 34: Six parts of the house of quality, source (Bergquist & Abeysekera, 1996)

The major functions of QFD were development and production of products, analysis of client requirements and management of quality. Subsequently, the functions of QFD have been extended from its original concept to other areas including design, management, timing, maintenance, decision-making, and management process. Indeed, it has been widely used for decision-making (Van De Poel 2007; Prior and Akao 1967; Raissi et al 2011). The QFD method has been widely applied to three main aspects of decision-making: estimation, selection, and evaluation (Chan & Wu, 2020). It is commonly employed to make trade-offs between different design alternatives.

Given that this is a new application, the traditional QFD structure with the four houses is not applicable in our context. However, we will focus mainly on the second QFD matrix that binds the design objectives to the system components alternatives, corresponding here to the project objectives and the decision alternatives. In our case, the nature of alternatives to be addressed in the QFD include not only conceptual alternatives, but also contractual strategy alternatives, local content strategy alternatives, etc.

The upper part of the QFD allows us to study the compatibility of the relationships between the decision alternatives, since it must be quantified to make rigorous trade-off decisions. The lower part allows for evaluating them concerning their contribution to the project objectives. Finally, the decisional part allows for evaluating the possible solutions by selecting and assembling one alternative per decision. That will allow for building scenarios based on several interdependent alternatives while considering their performance and compatibility.

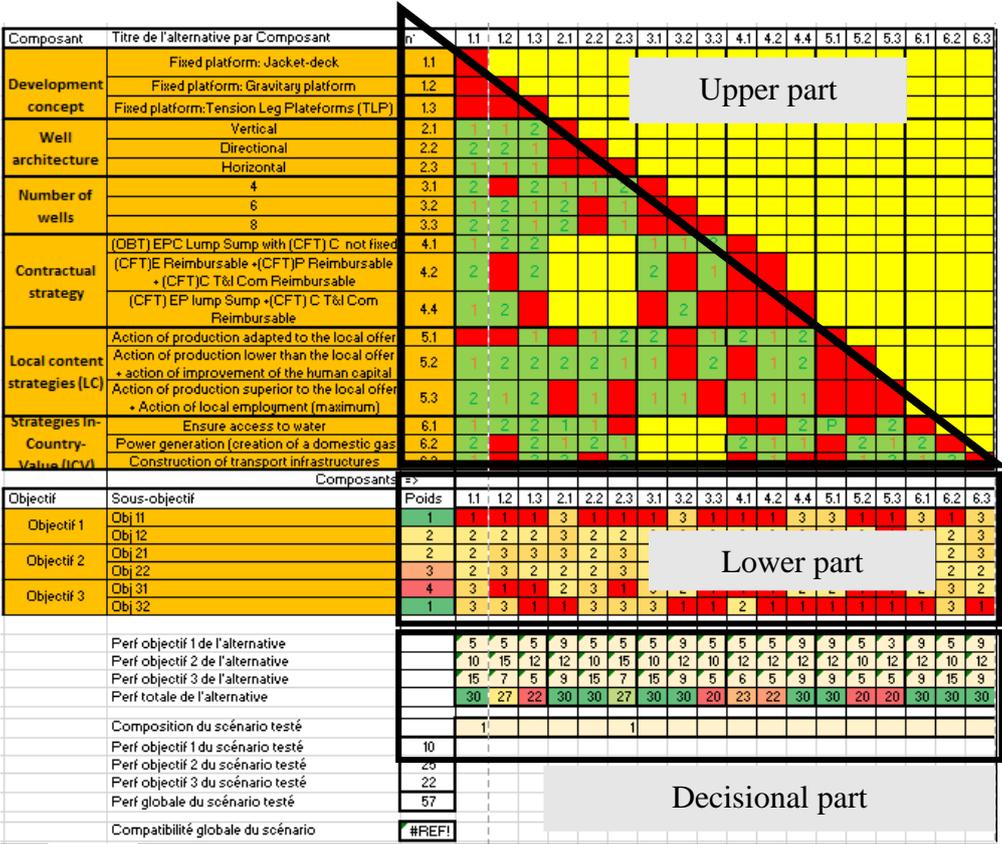


Figure 35: Second QFD matrix "roof of the house"

The following paragraph will present existing applications of QFD approach in similar contexts.

4.3.2 Applications of the QFD in our context

It has been deployed, in product design decisions to select the best design alternative (Cook & Wu, 2001; Delano et al., 2019), to design a liquefied petroleum gas (LPG) cylinder trolley (Al amin et al., 2015), and in location decisions to select facility sites (Chuang, 2001). For instance, Celik and co-authors extended the principles of Quality Function Deployment (QFD) to address investment decisions in maritime transport. Some modifications were made to ensure that the proposed mechanism could be adapted to this type of decisions (Celik et al. 2008).

Several applications of the QFD model have been carried out in different areas. According to (Chan & Wu, 2020)'s literature review over QFD applications, QFD has been successfully applied in 22 different countries in addition to new product development (NPD) processes in various sectors of the manufacturing industry, such as automotive, service, telecommunications, transport, and electronics.

Moreover, it has been proven that the QFD method can be applied to construction projects as a tool to address the most important client requirements from the beginning and to improve the indicators that support project success (Delgado-hernandez et al., 2007).

According to research by Chan and Wu (2002) on the application of QFD, in developed countries such as Japan, the United States of America, the United Kingdom, and Canada, QFD is seen as a tool to identify and address problems encountered early in a construction project (Chan & Wu, 2020). As an example, QFD was applied to a real construction project in Indonesia, consisting of the reconstruction of a tunnel along a crude oil pipeline, as a control tool during the construction phases. It was found that the validity and applicability of the QFD model was fully confirmed (Paska, 2015).

It has also been used in oil and gas projects to evaluate and select suppliers. The purpose of using QFD is to enhance performance and reduce lead times in such projects (Jannatipour et al., 2015). It has additionally been used for the selection of the decarbonization scenario for oil shale processing in Estonia (Eldermann et al., 2017). It has been implemented to improve the quality maintenance management for the Upstream Oil and Gas Industry (Dzulyadain et al., 2021). The application of the QFD method has been extended to include evaluating environmental performance in an offshore oil and gas development case from the perspective of decision makers (M. Yang et al., 2011) and improving the quality of maintenance services at offshore facilities (Zulfikar & Singgih, 2021).

Moreover, Akbas and Bilgen have provided a summary of the application of QFD in the energy and environmental fields (Akbaş & Bilgen, 2017). Some of these applications in the energy field include the development of environmental indicators for offshore oil and gas activities (M. Yang et al., 2011), for energy security operations in the domestic gas sector (Shin et al., 2013), and for the implementation of energy improvements in buildings (Shao et al., 2014).

The application of QFD in the construction field was stimulated by the fact that there are similarities between the new product development (NPD) process and the construction process (Formoso et al., 2002). We are particularly interested in its application to decision-making in the field of construction and more specifically in the field of oil and gas development.

Although, to the best of our knowledge, no papers have been seen which propose the application of QFD for evaluating decisions alternatives in the context of oil and gas development projects.

#### 4.3.3 Advantages and limits

This tool has been shown to have many benefits in both the short and long term. According to (Singgih et al., 2013), the QFD approach can provide some short-term benefits, such as helping to change the corporate culture, decreasing late engineering changes, and reducing inter-department coordination challenges. Indeed, a better coordination between the different work departments facilitates multidisciplinary teamwork and improves communication between decision-makers during the early stages of the development process through teamwork (Revelle et al., 1998).

Cohen (1995) argues that this method promotes more effective communication between the actors involved in the process in formulating possible solutions, which is an important aspect of project success.

Indeed, communication in the management of construction projects such as oil and gas development projects involve the participation of different parties and maintaining a QFD can help to involve all these parties from the beginning (Oakland and Marosszeky, 2006).

Furthermore, this approach allows to better justify the choices made to actors who are not involved in the decision-making process, then to better document and trace the complete path of decisions taken. Respondents from construction companies familiar with this method reported that it is effective in identifying and prioritizing customer requirements, building trust between customers and construction companies, improving customer satisfaction, and facilitating communication (John et al., 2014). This ease of communication is achieved through the exchange and transfer of information as well as experience between different members of the team. “It broke the communication barriers between project stakeholders and project manager as well as among the team members” (Paska, 2015).

Significant long-term benefits of the QFD approach are reduction in development time, reduction in design cost, increased productivity and company profits (Cohen, 1995).

In turn, there are some limitations. The main problems that companies using the QFD may encounter are due to a lack of experience in using the methodology (Revell & Cox, 1997). This can lead to difficulties in collecting information, handling large matrices, evaluating objectives, etc. Therefore, it may require a team facilitator who is familiar with the methodology and can manage a team (Govers, 1996).

#### 4.3.4 An example of an algorithm that can be applied for scenario generation

For morphological or QFD approaches, exploring and then deducing a list of all the plausible scenarios can be difficult to do manually, which may discourage some decision makers from using these approaches. It therefore appeared necessary to automate the process of identifying plausible scenarios, and even estimating their characteristics (global compatibility score, global performance score, etc.).

We have proposed to develop a dedicated algorithm to perform these tasks. This algorithm considers as input data an Excel file containing the DA-DA and the PO-DA matrices. The consideration of the DA-DA matrix is the key since it expresses the compatibility between the decision alternatives, which allows for plausibility to be assessed. As for the PO-DA matrix, it permits the estimation of the performance score of each identified scenario.

To deduce the list of plausible scenarios, the developed algorithm can follow the above steps.

**Step 1: extract the necessary data from the input file.** The compatibility indices introduced in the DA-DA matrix can be expressed in numerical values to facilitate the calculation of the compatibility score.

**Step 2: construct recursively a directed acyclic graph (tree).** Each node presents an alternative of a specific decision, and each edge  $u \Rightarrow v$  between two decisions alternatives means that the alternative  $v$  is compatible with the alternative  $u$  with index of compatibility Cost  $C$ .

For the  $N$  decisions in the matrix DA-DA, the algorithm will start with the first alternative of the first decision ( $D_{11}$ ) and identify the alternatives of the next decision ( $D_{2j}$ ) that are compatible with it. This step is detailed in Figure 36.

For each pair of alternatives identified, a new edge is created in the graph. This process is repeated until all decisions alternatives in the graph are studied. This allows to build a graph representing all the possible paths.

**Step 3: Run DFS (Depth First Search) algorithm over the graph.** This step allows to iterate over all paths of the graph and detect plausible scenarios. Each scenario is defined as a path in the graph starting from the root, passing through  $N$  nodes until a leaf of the graph, where  $N$  is the total number of decisions. In other words, if the number of the nodes of a given scenario is not equal to the total number of decisions, then the path is not valid.

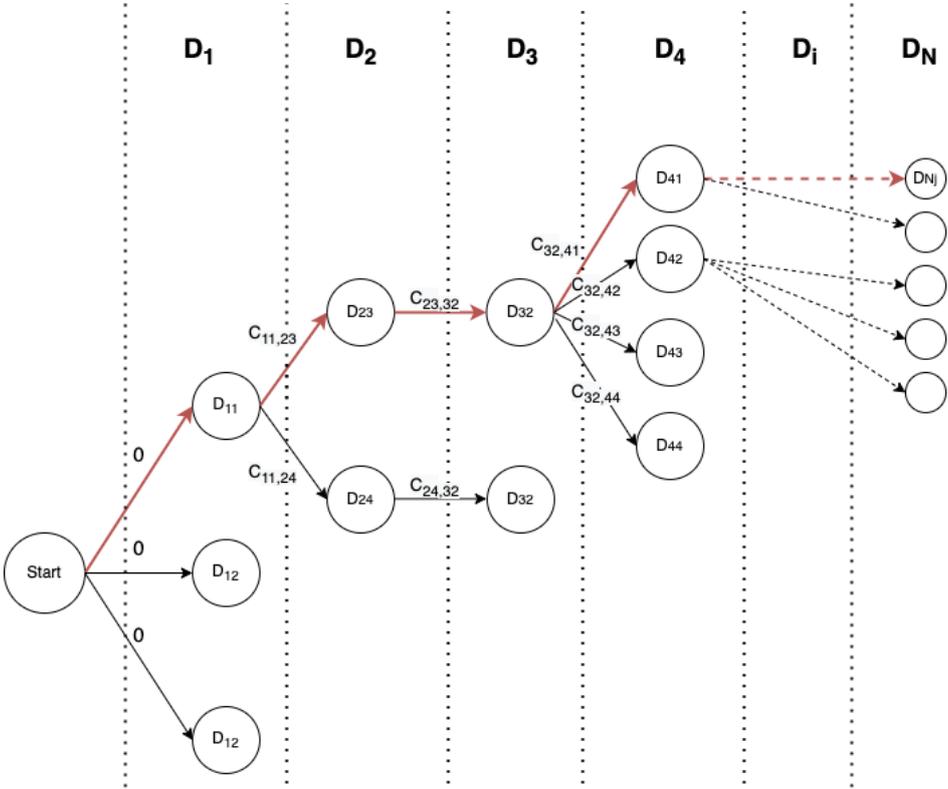


Figure 36: Illustration of step 2

The principle of this algorithm is detailed in the following pseudocode

```
Function build_graph(current_decision):  
  BEGIN  
    for each current_alternative in current_decision:  
      for each alternative in current_decision + 1:  
        if matrix[current_alternative][alternative]  $\neq$  -1 (compatible solution):  
          add_Edge (current_alternative -> alternative)  
  
    build_graph(current_decision + 1)  
  END  
  
current_decision = 1  
build_graph(current_decision)  
  
scenarios = []
```

```
Function DFS(current_node, iteration, current_scenario):  
  BEGIN  
    if(number of childs(current_node) == 0 AND iteration == N):  
      print("valid path from root to current_node")  
      scenarios.add(current_scenario)  
    for each child in childs(current_node):  
      current_scenario.add(child)  
      DFS(child, iteration+1, current_scenario)  
      current_scenario.remove(child)  
    END  
  
DFS(0, 0, [])
```

```
Function compatibility_score():  
  BEGIN  
    for each scenario in scenarios:  
      scenario_score = 0  
      for each alternative_i in scenario:  
        for each alternative_j in scenario (where j>i):  
          scenario_score = scenario_score + matrix[alternative_i][alternative_j]  
  
  END
```

#### 4.3.5 Intermediary synthesis about matrix-based approaches

Since morphological and QFD approaches are similar in terms of information (DA-DA and DA-PO) and different in terms of process (2 successive mono-criterion filters for morphological, 1 single bi-criteria filter for QFD), it seemed useful at this stage to propose an overview of the main strengths and weaknesses of these two methods (see the following Table 9). This table provides elements allowing to justify the choice of a matrix-based structuring methodology.

After these two matrix-based strategies, a third one, possibly lighter albeit less precise, is proposed in the following section.

Table 9: Strengths and weaknesses of the two structuring methods studied

	Strengths	Weaknesses
Morpho	<p>Encouraging discussion and debate, especially in the synthesis phase.</p> <p>Helping to overcome the cognitive difficulties faced during scenario development and selection (Pereverza et al., 2017).</p> <p>Developing a set of plausible scenarios can help to explore all possible scenarios without bias or prejudice and avoid selecting common scenarios that may not be relevant to the new case study.</p> <p>Being a valuable tool for oil and gas projects, as each host country has its own regulations and conditions.</p> <p>Allowing to reduce problems related to the lack of transparency, traceability, and clarity in both the scenario development and selection process (Johansen, 2018; Ritchey, 2012)</p>	<p>Synthesizing the scenarios may appear to some as a potential source of confusion and error if the identification of the scenarios is done manually.</p> <p>Implementing this method may require a specific computer tool that can facilitate this task (Eriksson &amp; Ritchey, 2002; Ritchey, 2011).</p>
QFD	<p>Improving communication between the actors involved in the process of formulating possible solutions (Cohen, 1995; Oakland &amp; Marosszeky, 2006; Paska, 2015; Revelle et al., 1998).</p> <p>Facilitating communication and interaction between construction companies and the target client, which can help overcome problems associated with a lack of identification and prioritization of client needs during project definition (John et al., 2014).</p>	<p>Experiencing difficulties arising from a lack of experience in using the methodology (Revelle et al., 1998)</p> <p>Difficulties in collecting information, handling large matrices, evaluating objectives.</p> <p>Implementing this method may require a team facilitator who is familiar with the methodology and can manage a team (Govers, 1996)</p>
Both	<p>Using a matrix format that can easily be exploited for other manipulations.</p> <p>Being adaptable to solve complex problems, especially those involving actors from different fields of expertise (Ritchey, 2011).</p> <p>Facilitating collective or synchronous decision-making requiring a high level of interaction between decision-makers (Pereverza et al., 2017).</p> <p>Reducing challenges associated with poor coordination between the different work departments (Singgih et al , 2013).</p> <p>Allowing to better justify the choices made to actors not necessarily involved in the decision-making process, then to better document and trace the complete path of decisions taken.</p> <p>Identifying new opportunities while minimizing costs before proceeding to the design phase and reducing the time spent on engineering studies (Goel et al., 2019)</p>	<p>Conducting a QFD can be time consuming and resource intensive, including assessing consistency (Johansen, 2018).</p> <p>Relying on subjective assessment (Elmsalmi et al., 2021).</p>

#### 4.4 Building visual scenarios (with a graph-based approach)

The objective of this section is to build visual plausible scenarios with good relevance, using the DA-DA graph. Other information about performance of decision alternatives may be included in the graph or available on another support.

##### 4.4.1 The basic graph representing compatibility links between decision alternatives

The decision graph shown in Figure 37, composed of 7 decisions ( $N=7$ ,  $M$  is unknown) and a reduced number of edges and alternatives, is used to illustrate this purpose. This graph displays D-D and D-DA.

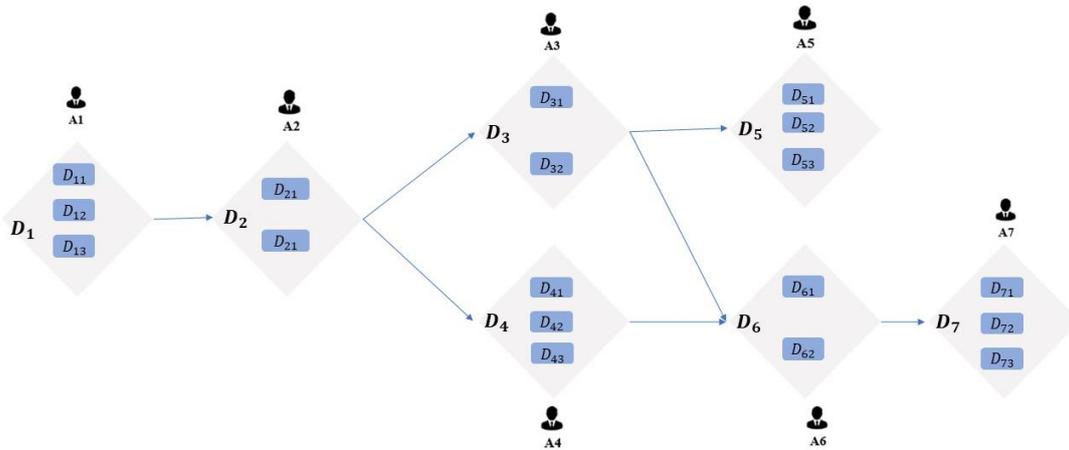


Figure 37: A network of interdependent decisions (D-D), each with its own alternatives (D-DA)

Thus, individual interactions between alternatives are displayed, introducing DA-DA (see Figure 38). To visualize the degree of compatibility between the nodes (or decision alternatives), three colors are used to represent the value of the links between these nodes. A red link between two nodes indicates that the two decision alternatives in question are not compatible, an orange link indicates that this combination is not preferred but not blocking, and a green link indicates that they are completely compatible. For each pair of interdependent decisions, all possible combinations are listed including pairs of alternatives that are compatible, not preferred, and not compatible.

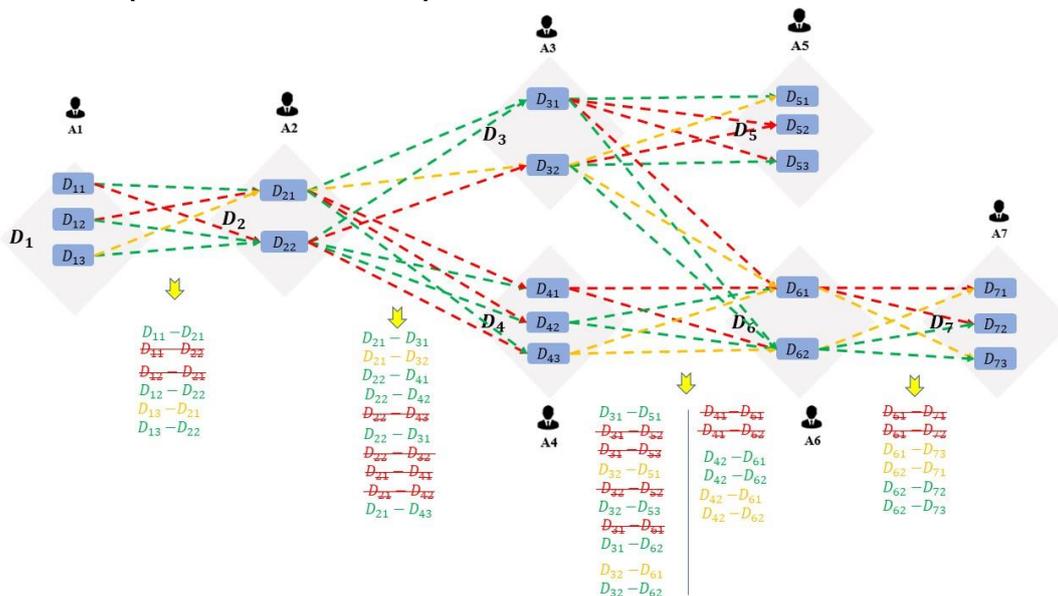


Figure 38: Decision alternatives graph (DA-DA)

#### 4.4.2 Reshaping the graph to highlight good compatibility and remove bad compatibility

This visual representation of interdependencies at the level of alternatives allows for developing heuristics that can be applied during meetings. The aim is to be able on live, during a meeting, to explore different assumptions, like the level of requirement for compatibility (green only or orange allowed) and the initiating node (which decision is made first).

In the specific case of making 1 decision among  $N$ , there are thus less possible scenarios since the starting points will be the different alternatives for this initial decision.

Before that, it is useful to put closer in the graph nodes with green edges (strong compatibility). This gives a preliminary idea of feasible “paths” assembling compatible alternatives to form a complete scenario. An illustration is given below in Figure 39. For instance, when  $D_{1,1}$  has only one green edge with  $D_{2,1}$ , it is moved to be closer from  $D_{2,1}$ .

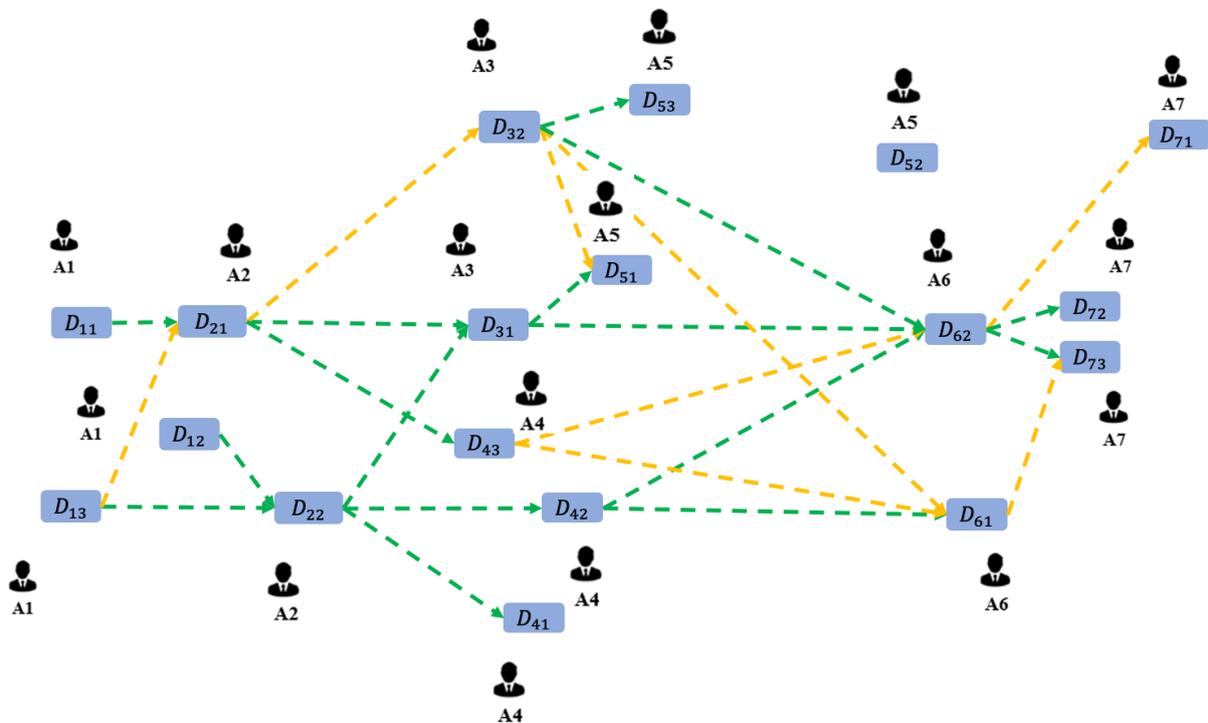


Figure 39: simplification of the interdependencies between alternatives by excluding red edges

The next step is to identify pre-assemblies, with 2-uples or 3-uples, as shown in Figure 40.

It must be noted that these pairs are not symmetrical. Choosing  $D_{7,2}$  implies choosing  $D_{6,2}$  (since  $D_{7,2}$  is not related with other alternatives of  $D_6$  with green or orange edges). However, choosing  $D_{6,2}$  does not imply to choose  $D_{7,2}$ , since  $D_{7,3}$  is also possible (even  $D_{7,1}$  if the requirement is “orange allowed”).

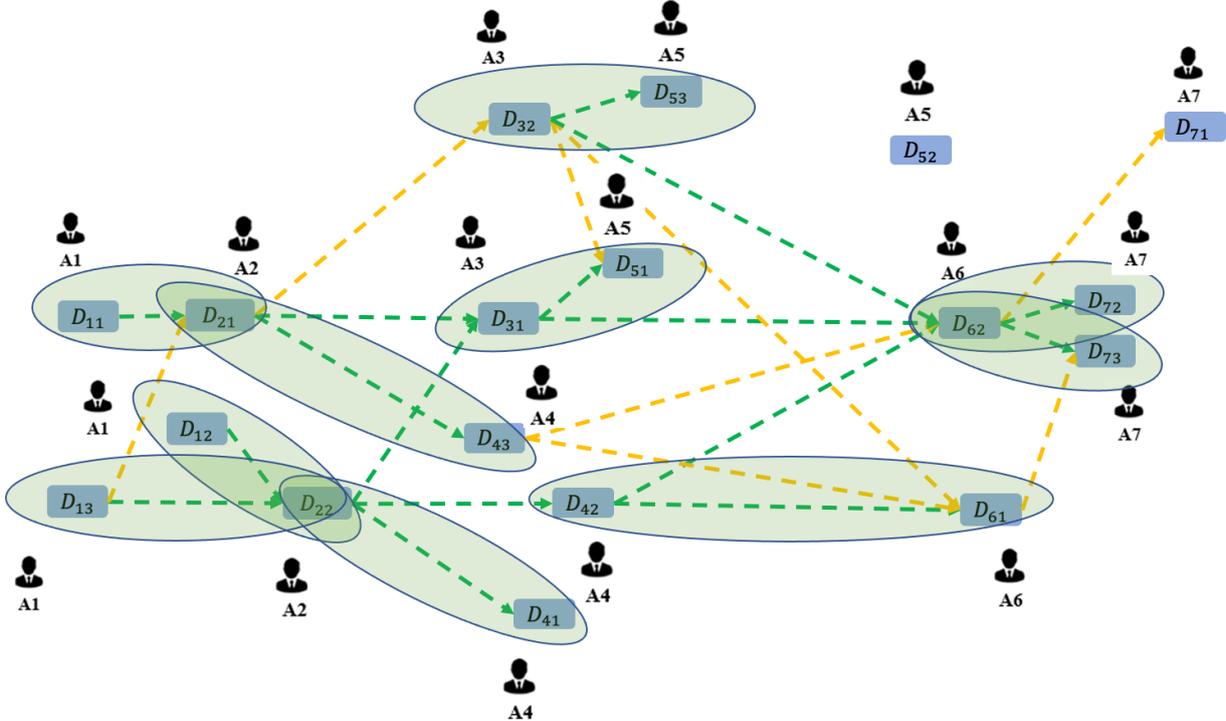


Figure 40: pre-identification of coupling oriented relationships between pairs of alternatives

It is now possible to propose a structured way to get plausible scenarios in a reasonable time. We consider a practical situation of a meeting with the actors involved in this network. To simplify, we consider that  $P = N = 7$ . It is possible since  $N$  is low enough.

4.4.3 An example of heuristics that can be applied during a decision meeting

For preparing a future validation committee, the following procedure can be applied.

**Step 1: detect highlights in the generic network** (Figure 37). For instance, as shown in Figure 37, there are some “dead ends” in the network:  $D_1$  is only related to  $D_2$ ,  $D_5$  is only related to  $D_3$ , and  $D_7$  is exclusively related to  $D_6$ .

**Step 2: detect specific distribution of colors in this network** (Figure 38). Isolated nodes are the easier to treat since they are screened out.  $D_{5,2}$  is not related to anything else with a green or orange edge, so it is not possible to find a feasible scenario including  $D_{5,2}$  whatever the requirement level. Similarly,  $D_{4,1}$  has an interaction with  $D_6$ , but no alternative of  $D_6$  has a green or orange edge with  $D_{4,1}$ .

$D_{4,3}$  is connected to  $D_{2,1}$  only, but moreover it is connected to  $D_6$  with orange edges only ( $D_{6,1}$  or  $D_{6,2}$ ). This implies that a strong level of requirement on compatibility will eliminate  $D_{4,3}$ .

Similarly,  $D_{6,1}$  relates to  $D_3$  and  $D_7$  with orange edges only.

**Step 3: propose different scenarios with different compatibility requirement levels and different starting points** (Figure 40). Two main strategies are possible: “green only” or “orange allowed”. Of course, a third category is always possible with a certain limit on the number of orange edges (maximum 2 orange edges).

As evoked previously, dead ends are important nodes to list, because if they are the initiating point of the scenario, then they put a constraint on at least one another node. For instance, with a “green only” strategy, starting with  $D_{1.3}$  implies  $D_{2.2}$ , then  $D_{3.1}$  and  $D_{4.2}$ , then  $D_{6.2}$ . A last choice must be made between  $D_{7.2}$  and  $D_{7.3}$ , but the essential of the scenario is constrained by the strategy and the initial choice of  $D_{1.3}$ .

Another instance starting with  $D_{5.3}$  implies choosing  $D_{3.2}$ , then  $D_{6.2}$ , then  $D_{4.2}$ , then  $D_{2.2}$ . Two choices are still possible, either  $D_{1.2}$  or  $D_{1.3}$ , and  $D_{7.2}$  or  $D_{7.3}$ , but the main part of the scenario (5 decisions on 7) is obtained with only the initial choice of  $D_{5.3}$ .

A third example with  $D_{1.1}$  as a first decision implies  $D_{2.1}$ , then  $D_{4.3}$ , the 3-uple ( $D_{3.1}$ ,  $D_{5.1}$ ,  $D_{6.2}$ ). A choice has to be made between  $D_{7.2}$  and  $D_{7.3}$ , but there are only two possibilities and 6 decisions on 7 are constrained by the initial choice.

On the opposite, choosing an “orange allowed” strategy may open far more possibilities. For instance, with  $D_{1.3}$ , it is not mandatory any more to choose  $D_{2.2}$ .

Starting by  $D_{1.1}$  for instance still implies to choose  $D_{2.1}$ . However,  $D_{2.1}$  may now be associated with  $D_{3.2}$ , itself having two choices related to  $D_5$  ( $D_{5.1}$  or  $D_{5.3}$ ) and two choices related to  $D_6$  ( $D_{6.1}$  or  $D_{6.2}$ ).  $D_{6.1}$  implies  $D_{7.3}$ .  $D_{6.2}$  has now 3 possible connections with  $D_7$ . This means that we now have 10 possibilities instead of 2 with the green only strategy.

Another example is by starting by  $D_{2.2}$ , which looks more like a hub, with multiple possible connections.  $D_{2.2}$  may be associated with  $D_{1.2}$  or  $D_{1.3}$ . On the other side, it must be associated with the couple ( $D_{3.1}$ ,  $D_{5.1}$ ), with  $D_{4.2}$  (it has a green link with  $D_{4.1}$  but this one cannot be associated with  $D_6$ , so this path is eliminated). Moreover, it can be associated with  $D_{6.2}$  or ( $D_{6.1}$ ,  $D_{7.3}$ ).  $D_{6.2}$  can be associated with any the three alternatives of  $D_7$ . This means that we have 24 possible scenarios, which may now be too much for assisting selection.

This is only a small fictitious example, but it serves to illustrate the possible advantages and drawbacks of each strategy: for the “green only” strategy, we may have very few or even no possible scenario. For the “orange allowed” strategy, we may have too many scenarios but once again the principle to explore step by step during a meeting could help to progressively make choices at important switches. Finally, the hybrid strategy (for instance, 2 orange edges allowed) could theoretically help to get an intermediary number of scenarios but could be practically more difficult to implement. Namely, it is difficult to know in advance the correct maximal number of orange edges, and secondly it may be difficult to anticipate at the beginning of the construction of a scenario if we are in a deadlock.

#### 4.4.4 Extending the proposal by using the concept of stratified decisions

Since making decisions for a distant future is always challenging and uncertain (W. Zeng et al., 2018), an innovative way of thinking, called stratified decisions or stratified approach has been recently proposed and is quickly applied in our context.

In the classical stratified approach, multiple possible states are considered to represent the occurrence of the events and their combinations (Asadabadi et al., 2018). Here, the notion of event corresponds to selecting a decision alternative. Then, the states are placed in successive strata, the number of strata depending here on the number of decisions (Figure 41).

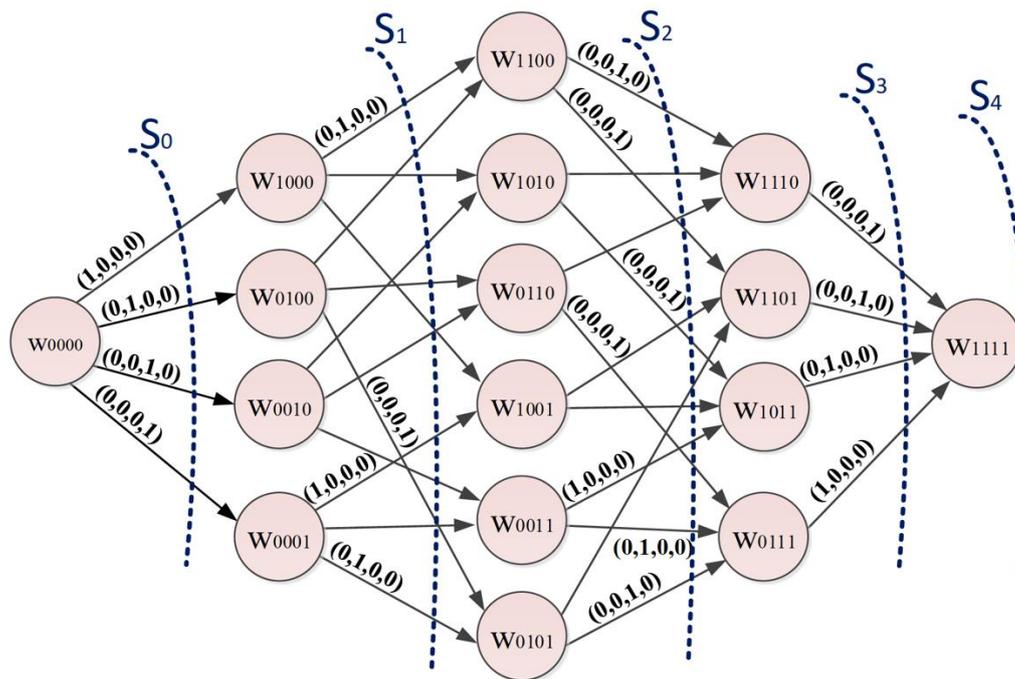


Figure 41: illustration of a generic stratified approach with all possible combinations

The subtlety is here to use the incremental enlargement principle proposed by Zadeh to prevent the creation of “useless” states and limit this creation to states with possible future paths (Zadeh, 2016). We make the distinction between possible in the strict meaning of feasibility of the path and plausible with the additional meaning of value of this path. A path of events is here the sequence of progressive decision-making about the  $P$  decisions. It is a  $P$ -long path.

At each step of the previous heuristics, the next strata are developed, giving progressively details about possible paths and removing impossible paths (Figure 42).

It is recalled here that with 7 decisions having 3 alternatives each, we already are in a huge decision-making problem with  $3^7$  scenario alternatives. The notion of compatibility and exclusion of incompatible alternatives drastically reduces the number of possible scenarios. Moreover, this progressive opening on possible paths at each decision is even more interesting for practical use in industrial context. It may notably allow for having bigger gaps between  $P$  and  $N$ , knowing that we could build a  $P$ -long path with a vision of the possible branches considering the  $N-P$  other decisions (pure anticipation of possible future paths without having to decide about them today).

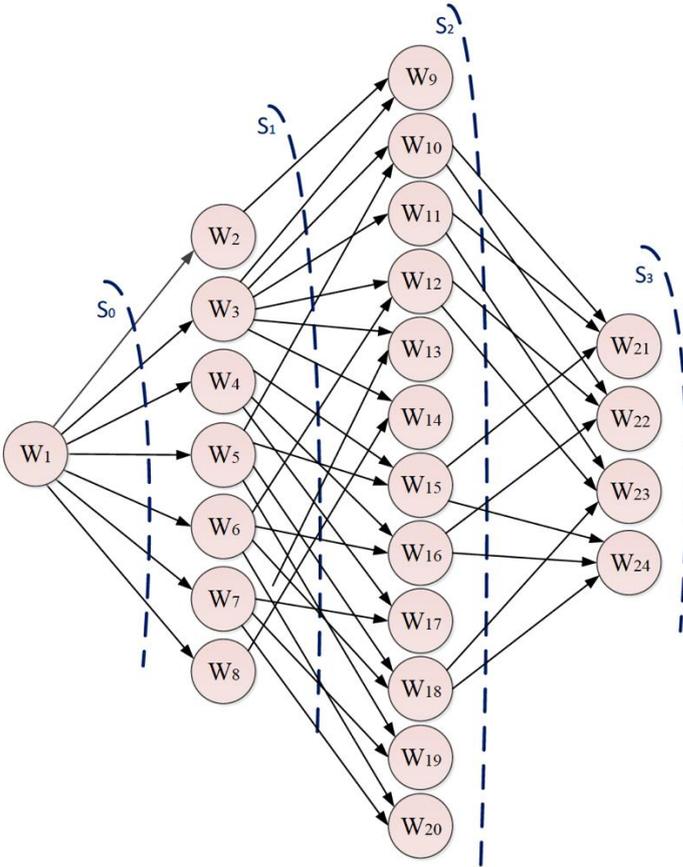


Figure 42: illustration of a reduced stratified approach, where paths at stratus  $N+1$  depends on decisions at stratus  $N$  (and before)

This idea is still under development, notably on the practical applicability. An information system dedicated to such multi-decision meetings could be developed, this will be a point in the Perspective section in Chapter 7.

#### 4.5 Chapter conclusion: how to choose an appropriate scenarios generation approach?

Throughout this chapter 4, the second step is presented which aims at structuring the problem to propose relevant and plausible scenarios assembled from elementary decision alternatives.

Three possible strategies have been presented, combining scenario plausibility (based on decision alternatives compatibility) and relevance on three different ways: sequentially (corresponding to the morphological approach), simultaneously (corresponding to the Quality Function Deployment approach), and hybrid (corresponding to a step-by-step heuristic for exploring graphs of decision alternatives and their interdependencies).

The choice between these strategies depends on decision makers' preferences and constraints. Preferences are about the consideration of both key scenario assessment parameters, plausibility, and relevance. They may prefer building plausible and then relevant scenarios or simultaneously plausible and relevant scenarios.

In doing so, we argue that the challenges that arise from poor coordination between decisions will be mitigated, since interdependencies between decision alternatives are taken into account. This is especially true for decisions that are highly interdependent and require a high level of interaction between their decision makers.

We also argue that all approaches allow for the generation of relevant and plausible scenarios while minimizing costs before proceeding to the design phase, reducing the time spent on engineering studies and backtracking during this phase.

Further, the three proposed approaches will improve the transparency of the entire decision-making process and allow for better explanation of the choices made to stakeholders who are not directly involved in the decision-making process.

## 5 Chapter 5: Solving the problem by selecting and recommending scenarios

This Chapter introduces the third step of the proposed decision-making process which is about solving the multi-decision problem. It consists of selecting a scenario selection technique among three possible families of strategies.

## 5.1 Chapter introduction: the need for an adequate scenario selection and recommendation technique

After scenario identification it is still unclear which of the possible scenarios should be retained. A multi-criteria decision analysis (MCDA) should be applied to evaluate each of them and choose the best one. For the QFD approach, MCDA should be applied to evaluate and select the best scenario considering the performance and compatibility of its components. However, for the morphological analysis, it should be applied to evaluate and select the best scenario considering only the performance parameter, since a set of plausible scenarios has already been identified by the compatibility matrix. A literature review on evaluation methods (MCDA) is presented in the following.

The MCDA methods are part of operations research dealing with complex decision-making problems involving numerous alternatives and criteria (Almulhim, 2014). Several MCDA methods have been developed to deal with complex decision problems encountered in petroleum engineering. This has led to an increase in the application of these methods in recent years.

In particular, in an upstream decision-making problem, multiple technical and non-technical attributes must be considered, including technical, financial, environmental, societal, and even geopolitical attributes. According to Shafiee and co-authors, these methods are capable of simultaneously handling more than one attribute involved in an upstream decision-making problem. Such problems include “selecting the best drilling techniques and vessels, choosing the most appropriate maintenance strategies for different systems and components on oil and gas platforms, determining the most environmentally friendly end-of-life strategies for wells, identifying the most viable decommissioning processes for facilities, etc.” (Shafiee et al., 2019).

The MCDA methods are classified into three families, from the simplest to the most elaborated ones. In the following, a description of each of these families, highlighting their advantages and disadvantages, is presented.

## 5.2 Family #1: the absolute compensatory methods

Among these methods, we can cite the weighted geometric mean and the weighted sum model (WSM), also known as Simple Additive Weighting (SAW). However, the WSM method is only detailed below.

The WSM is the oldest and among the most popular methods for solving multi-criteria decision-making problems (Salehi & Izadikhah, 2014). The single-criterion synthesis methods also known as weighted linear combination or scoring methods are based on the additive model.

It allows for compensation between criteria so that advantage in one criterion can counterbalance a disadvantage in another (Martins et al., 2020a). It is the most popular and simplest multi-criteria decision analysis method for evaluating alternatives based on a set of decision criteria (Sorooshian, 2015). To perform its calculations, the SAW method considers only the weights of the criteria and the additive form.

It evaluates the alternatives according to a unique score composed of a weighted sum of the criteria evaluations. This score is calculated by multiplying the scaled value given to the alternative of that attribute with the relative importance weights assigned by the decision maker, and then aggregating the products for all criteria (Shafiee et al., 2019; Sorooshian, 2015). The alternative with the highest score is considered the most suitable.

Suppose that a given problem is defined over  $p$  alternatives and  $m$  decision criteria. Let us then assume that  $w_j$  denotes the weight of the relative importance of criterion  $C_j$  and  $a_{ij}$  the performance value of alternative  $A_i$  when evaluated against criterion  $C_j$ . Thus, the aggregate importance of alternative  $A_i$  is defined as  $A_{i\ score}$  as follows:

$$A_{i\ score} = \sum_{j=1}^n w_j a_{ij} \quad \text{Equation (1)}$$

The WSM has been applied in the oil and gas, nuclear and mining sectors to solve decommissioning problems. In addition, the energy sector is one of the sectors in which it was used for several reasons. For further details see the research work of Martins and his co-authors (Martins et al., 2020a).

According to Afshari and co-authors, “the advantage of this method is that it is a proportional linear transformation of the raw data, which means that the relative order of magnitude of the standardized scores remains equal” (Afshari et al., 2010). Another advantage is the simplicity of its calculations and the absence of complex computer programs (Martins et al., 2020a). This makes it ideal for users with limited mathematical background. According to Sorooshian, this method is “more mathematical user friendly and more suitable for design makers with less mathematical knowledge” (Sorooshian, 2015).

However, as indicated by (Martins et al., 2020a), since it allows for trade-offs between criteria, it is important to ensure that critical issues are not neglected. As such, the results of this method do not always reflect reality as they may be illogical.

5.3 Family #2: the relative pairwise comparison methods

The comparative compensation methods allow trade-offs between criteria. That means that alternatives that present a deficiency in one or more criteria can be compensated for by their performance in other criteria, allowing for more realistic and subtle modeling (Greene et al., 2011). These methods provide a relative score in the final that helps decision-makers decide. Among these methods, we mention here the Analytic Hierarchy Process (AHP).

5.3.1 Analytic Hierarchy Process (AHP)

Another way to rank alternatives is to use the AHP. It was developed by the famous American operational researcher Tomas L. Saaty in the 1970s to cope with complicated decision-making processes. It has been widely studied and improved since then (Saaty, 1980). The AHP is a decision-making procedure that “combines mathematics and psychology in order to be able to select the best alternative”(Shahsavari & Khamehchi, 2018). It provides a comprehensive and rational framework for structuring a decision and establishing priorities and weights for alternatives by organizing objectives, criteria, and sub-criteria in a hierarchic structure (Bernasconi et al., 2010). This approach, according to Saaty (1980), has three major steps detailed below.

**Step 1:** to deal with the complexity of a decision-making process, a decomposition of the decision problem in question into a hierarchical structure of sub-problems that can be analyzed independently, is necessary. As shown in the Figure 43, this structure is built top-down: the decision objective is placed at the top of this hierarchical structure, followed by the criteria (objectives) and sub-criteria (sub-objectives) for evaluating the alternatives and then the alternatives.

For the example shown in the following figure, the objective is to design oil and gas route. Pipeline influence criteria include slopes, geological conditions, and surface features. And each includes different sub-criteria. Indeed, such structure is necessary in order to identify the criteria and alternatives that are truly relevant (Russo & Camanho, 2015). It also enables to reject alternatives that are considered irrelevant or that do not satisfy the selected criteria.

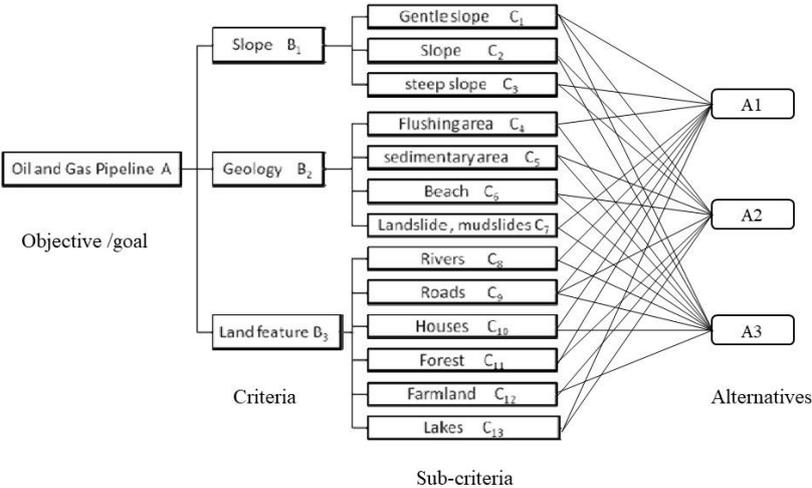


Figure 43: Hierarchical structure of decision, source (Russo & Camanho, 2015)

**Step 2:** evaluate the relative importance of the various decision criteria and alternatives by obtaining a judgment based on a set of pairwise comparison matrices. An example of these matrices is shown in Figure 44 and Figure 45.

A numerical or verbal scale is used in this comparison to demonstrate “how many times more important or dominant one element is over another element with respect to the criterion or property to which they are compared” (Saaty, 2008). This can be done by using Saaty's 1-9 scale of pairwise comparisons. It goes from "equal importance" corresponding to number 1 to "extreme importance" corresponding to number 9. Then, a relative weight is assigned to all the elements of the hierarchy and a hierarchy of their relevance is constructed (Russo & Camanho, 2015).

In this step, the maximum Eigen value, consistency index CI, consistency ratio CR are calculated to judge the consistency of each pairwise comparison and to confirm the reliability of the results (Shafiee et al. 2019). A decision can be made based on the normalized values if these values are found to be satisfactory. If not, the procedure is then repeated until they are satisfactory (Vaidya & Kumar, 2006).

<b>A</b>	<b>B<sub>1</sub></b>	<b>B<sub>2</sub></b>	<b>B<sub>3</sub></b>
<b>B<sub>1</sub></b>	<b>1</b>	<b>3</b>	<b>2</b>
<b>B<sub>2</sub></b>	<b>1/3</b>	<b>1</b>	<b>1</b>
<b>B<sub>3</sub></b>	<b>1/2</b>	<b>1</b>	<b>1</b>

Figure 45: Pairwise matrix of layer B to layer A, source (Russo & Camanho, 2015)

<b>B<sub>1</sub></b>	<b>C<sub>1</sub></b>	<b>C<sub>2</sub></b>	<b>C<sub>3</sub></b>
<b>C<sub>1</sub></b>	<b>1</b>	<b>3</b>	<b>5</b>
<b>C<sub>2</sub></b>	<b>1/3</b>	<b>1</b>	<b>2</b>
<b>C<sub>3</sub></b>	<b>1/5</b>	<b>1/2</b>	<b>1</b>

Figure 44: Pairwise comparison matrix of layer B to layer A, source (Russo & Camanho, 2015)

**Step 3:** calculate the priority weights to obtain the final priorities and ranking of the alternatives. The best alternative is the one with the highest value.

The applications of the AHP method are numerous and have been applied worldwide. Among its applications, we mention health care, conflict resolution, project selection, portfolio selection, budget allocation, architecture (Zahedi, 1986). It has also been used to model the interactions between risks in project management (Fang et al., 2010), assess the risks of construction projects (Dedasht et al., 2017), evaluate deep drilling applications (Sorooshian, 2015). AHP is one of the most commonly applied tools to energy problems, including oil and gas upstream and downstream industry, mining and nuclear (Martins et al., 2020b). Indeed, according to (Shafiee et al., 2019), different industries, such as oil and gas upstream and downstream industry, are solving their decision-making problems using this method given its different advantages. For instance, Wan and his co-authors applied this approach in oil and gas pipeline route selection (Wan et al., 2011). The goal was to quantify the importance factors involved in this decision making and reduce the impact of subjective factors. For more details on the different applications of AHP, a detailed review is provided by Vaidya and Kumar (Vaidya & Kumar, 2006).

One of the main advantages of AHP, as stated by (Almulhim, 2014), is its ability to handle multi-criteria decision-making problems such as planning, resource allocation, optimization, selection of the best alternative from a list of alternatives, etc (Vaidya & Kumar, 2006).

Another major advantage of this method lies in its hierarchical structure, which can easily be adapted to many complex problems. In addition, Shahsavari and Khamehchi noted that it is one of the MCDM methods that has been successfully applied in the oil and petroleum industry (Shahsavari & Khamehchi, 2018).

However, the high number of pairwise comparisons can be problematic. In addition, the method may encounter problems arising from the interdependence of the criteria and alternatives. Another disadvantage of AHP “is that it need deep mathematical understandings and knowledge” (Sorooshian, 2015). Thus, the ability of humans to analyze information can be a significant limitation to the use of AHP (Shih et al., 2007). Another point to note is that AHP has been used in many cases to primarily calculate the weighting of the criteria, while other techniques were preferred to evaluate the alternatives through TOPSIS or ELECTRE (Russo & Camanho, 2015).

5.3.2 Analytic Network Processes (ANP)

The Analytic processes developed by Thomas L. Saaty in the 1996’s, is a generalization of the AHP (Thomas L. Saaty, 2005).It uses a network structure instead of hierarchical structure to illustrates the dependence amongst the decision variables or criteria (hierarchy elements) (Zheng et al., 2017). This network structure is used mainly to overcome the limitations of the hierarchical structure (Dedasht et al., 2017).

Therefore, “ANP is an improved version of AHP to resolve problems with dependencies among criteria in a system that is divided into different decision clusters with each cluster containing several criteria” (Dedasht et al., 2017). In the following Figure 46, the different between AHP and ANP is clearly shown.

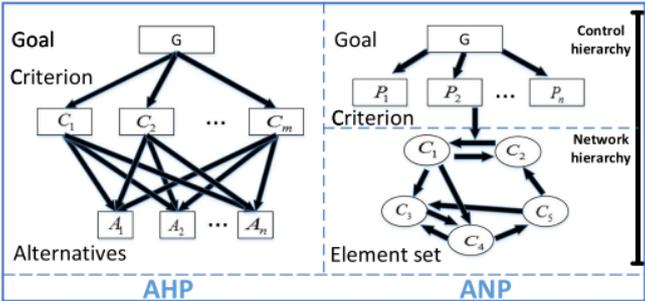


Figure 46: The relationship between AHP and ANP, source (Fei, 2020)

Like AHP, to rank the alternatives, it uses pairwise comparisons to evaluate the weight (priorities) of the elements composing the structure. The following four steps are involved in the ANP method (Dedasht et al., 2017).

**Step 1:** Perform the pairwise comparison using a pairwise comparison questionnaire between element interactions. The purpose of this step is to determine the relative importance of the criteria in achieving the objective.

**Step 2:** Build up the super matrix (W) using the priorities derived from the different pairwise comparisons obtained in the previous step. This matrix can be represented in a general form as

shown in Figure 47. Each component of this matrix is a submatrix ( $W_{ij}$ ), for which the columns represent the relative criteria of the elements of cluster  $C_i$  on each element of cluster  $C_j$ .

**Step 3:** Calculate the weighted super matrix. The matrix is first normalized by the sum to unity of each column. Then the unweighted super matrix is multiplied by the corresponding cluster priority to obtain the weighted super matrix.

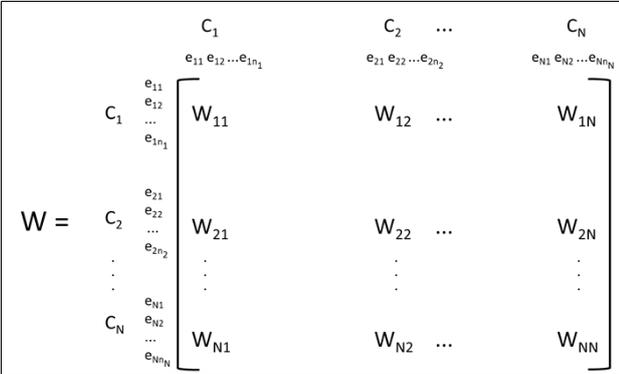


Figure 47: Graphic representation of the supermatrix generated in the ANP, source: (Saaty, 2008)

**Step 4:** The weighted supermatrix is increased to a sufficiently high degree of  $k$  until it is sufficiently stable to obtain ANP weights.

According to (Shafiee et al., 2019), ANP is one of several MCDA methods that have gained momentum in recent years in the upstream sector. For instance, Fazli and Mavi have been used ANP method for risk assessment in crude oil supply chains (Vosooghi et al., 2012). De Jesus and his co-authors, have been used ANP to select contracting strategies for oil and gas projects (De Jesus et al., 2019). The suggested network includes clusters of elements related to contracting strategy decisions. Such clusters include project characteristics, organizational structure, contract types, bidding process, alternatives. Dedasht and co-authors have been used ANP assess the relative importance of risk factors and to determine the best strategy for implementing a risk management program in the context of oil and gas construction projects (Dedasht et al., 2017).

Among the advantages of this method, we mention the fact that its structure is closer to reality because it allows to model the interdependencies between the elements while improving the transparency of the decision process (De Jesus et al., 2019). In addition, it has been shown to be very effective in solving problems in which there is dependence between criteria (Shafiee et al., 2019).

Nevertheless, none of this means that ANP is an ideal method, and among its limitations are the following. According to Almulhim, it “fails the task of studying dependency among the decision elements in MCDM problems under conditions of uncertainty” and it may not accurately reflect human preferences when the decision maker(s) cannot provide reliable data to assess the relationships between the elements (Almulhim, 2014).

## 5.4 Family #3: the relative comparison to reference point methods

The outranking methods are classified as non-compensatory (Barata et al., 2014). According to (Bouyssou, 2000), they provide a preference or outranking relationship between alternatives evaluated based on multiple criteria. Meaning that it provides a result of type alternative A outperforming alternative B, but without specifying how much. Among these methods, we mention below the Pugh evaluation method, TOPSIS, ELECTRE, and MR SORT.

### 5.4.1 The Pugh method

The Pugh matrix, a form of Decision Matrix proposed by Stuart Pugh, is a simple multi-criteria decision method used to solve decision problems involving multiple, often conflicting, objectives. The matrix columns present the alternatives, and the rows describe the criteria by which those alternatives can be evaluated (Frey et al. 2008).

However, compared to the traditional decision matrix shown in Figure , scales of 1 to 5 are rejected as they require absolute comparisons to objectives that might not be fully understood or stated and for each criterion, the alternatives are compared to a reference option or median option (Ullman, 2006). Figure 48 illustrates a decisional problem using the Pugh format. In this example, the vendor 1 is considered as a reference option. According to Frey and co-authors, this reference option should preferably be a well-understood option known for being generally very good (Frey et al., 2009).

It is common to use the following notation: the plus (+) score to indicate that the alternative is preferred over the median option, the minus (-) score to indicate that the alternative is less preferred than the median option, and the (S) same to indicate that the alternative is equal to the median option. The values +1, 0 and -1 can also be used to simplify the calculation process.

		Alternatives			
		Wt	Vendor 1	Vendor 3	Vendor 4
Criteria	Cost	.30		+	S
	Response time	.17		+	+
	Training time	.17		-	S
	Ease of use	.17		+	+
	Strong team	.10		-	-
	Team experience	.10		S	-
	Pluses	1.0		3	2
Minuses			2	2	
Overall total			+1	0	
Weighted total			+0.37	+0.14	

Figure 48: Example of the Pugh matrix (Ullman, 2006)

According to (Ullman, 2006), four scores can be generated using Pugh's formula: the number of positive points, the number of negative points, the overall total and the weighted total. The weighted total can be calculated by multiplying the sum of each score by the weight, where an S is counted as 0, each + is counted as + 1, and each - is counted as -1. The overall total is the difference between the number of positive points and the number of negative points. It represents an estimate of the decision makers' satisfaction with the alternative relative to the baseline.

This tool can be used in various contexts, such as product design, manufacturing system implementation, project site selection, or as part of a Lean-Six Sigma methodology. Indeed, according to (Ullman, 2006), most of the books and consultants recommend using Pugh's method to support the decision-making process for several reasons.

The main strengths of this method are highlighted in Ullman's book, they include: ease of understanding and implementation; flexibility because the user can easily add or remove alternatives or criteria without affecting the evaluation process; no need for advanced mathematical knowledge; a single score combining the evaluations, which allows decision makers to assess the relative value of each alternative separately (Ullman, 2006).

In addition, Shahsavari and Khamsehchi noted that it is one of the MCDM methods that has been successfully applied in the oil and petroleum industry (Shahsavari & Khamsehchi, 2018).

Further, this method provides better information for the participants to decide which alternative to select (Pugh, 1981). Nevertheless, like any other method, there are some limitations that need to be considered: inability to handle missing information, as all alternatives must be evaluated against all criteria; discriminating criteria that cannot be traded off are not manageable, as the total evaluation is measured as a sum or weighted sum (Ullman, 2006).

5.4.2 The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Technique for order performance by similarity to ideal solution (TOPSIS) identifies solutions from a finite set of alternatives. It was first introduced by Hwang and Yoon (1981) (Hwang & Yoon, 1981). Its basic principle is based on the determination of the relative proximity of an alternative to the optimal solution using the Euclidean distance. This implies that the chosen alternative must have the longest geometrical distance to the Negative Ideal Solution (NIS) and the shortest geometrical distance to the Positive Ideal Solution (PIS) (Ding et al. 2016; Shahsavari and Khamsehchi 2018). In the Figure 49 shown a graphical presentation, of the TOPSIS method, the white balls symbolize the alternatives, the gray ball the negative ideal solution (NIS) and the black ball the positive ideal solution (PIS).

Thus, the white ball that is closest to the black ball and furthest from the gray ball should be the best alternative of all (Vavrek & Chovancová, 2020). The “positive ideal solution is defined as the sum of all the best value that can be achieved for each attribute, while the negative-ideal solution consists of all the worst value achieved for each attribute”. (Rahim et al., 2018).

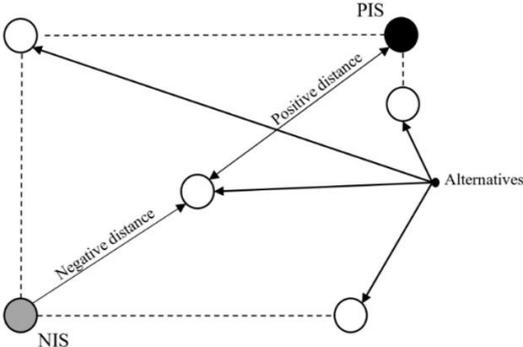


Figure 49: Graphical presentation of the TOPSIS method (Vavrek & Chovancová, 2020)

This method is composed of six steps (Alemi et al., 2011; Rao, 2007; Shahsavari & Khamehchi, 2018):

**Step 1:** create the decision matrix composed of  $m$  alternatives and  $n$  criteria. The number of alternatives and the number of criteria is respectively considered as the number of rows ( $i$ ) and columns ( $j$ ). The intersection of each alternative and criteria given as  $x_{ij}$ . Thus, we have a matrix  $(x_{ij})_{m \times n}$ .

**Step 2:** normalize this matrix using the following formula (Eq1), since in multi-criteria problems, the criteria have often inconsistent dimensions. The normalized matrix ( $R$ ) is constructed using the normalization method.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^m x_{kj}^2}}, \quad i=1, 2, \dots, m, \quad j=1, 2, \dots, n \quad \text{Equation (2)}$$

**Step 3:** calculate the weighted normalized decision matrix.

$$t_{ij} = r_{ij} \cdot w_j, \quad i=1, 2, \dots, m, \quad j=1, 2, \dots, n \quad \text{Equation (3)}$$

$$\text{where } w_j = \frac{W_j}{\sum_{k=1}^n W_k}, \quad j=1, 2, \dots, n \quad \text{Equation (3.1)}$$

So that  $\sum_{i=1}^n w_i = 1$  and  $W_j$  is the original weight to the indicator  $v_j, j=1, 2, \dots, n$

**Step 4:** determine the best alternative ( $A_b$ ) and the worst alternative ( $A_w$ ).

$$A_w = \{ \langle \max(t_{ij} \mid i = 1, 2, \dots, m) \mid j \in J_- \rangle, \langle \min(t_{ij} \mid i = 1, 2, \dots, m) \mid j \in J_+ \rangle \} \equiv \{ t_{wj} \mid j = 1, 2, \dots, n \},$$

$$A_b = \{ \langle \min(t_{ij} \mid i = 1, 2, \dots, m) \mid j \in J_- \rangle, \langle \max(t_{ij} \mid i = 1, 2, \dots, m) \mid j \in J_+ \rangle \} \equiv \{ t_{bj} \mid j = 1, 2, \dots, n \},$$

Where,

$J_+ = \{ j = 1, 2, \dots, n \mid j \}$  associated with the criteria having a positive impact, and

$J_- = \{ j = 1, 2, \dots, n \mid j \}$  associated with the criteria having a negative impact.

**Step 5:** calculate for each alternative  $i$  the geometric distances from the best alternative ( $d_{ib}$ ), and geometric distance from the worst alternative ( $d_{iw}$ ) in the following equations.

$$d_{ib} = \sqrt{\sum_{i=1}^n (t_{ij} - t_{bj})^2}, \quad i = 1, 2, \dots, m$$

$$d_{iw} = \sqrt{\sum_{j=1}^n (t_{ij} - t_{wj})^2}, \quad i = 1, 2, \dots, m,$$

**Final step:** calculate relative proximity of a given alternative  $i$  to the worst condition with the following equation and then rank the alternatives according to  $s_{iw}$ .

$$s_{iw} = d_{iw} / (d_{iw} + d_{ib}), \quad 0 \leq s_{iw} \leq 1, \quad i=1, 2, \dots, m$$

$s_{iw} = 1$  if and only if the alternative solution has the best condition; and

$s_{iw} = 0$  if and only if the alternative solution has the worst condition.

TOPSIS has been successfully applied to the areas of product design, manufacturing, quality control, location analysis and transportation (Shahsavari & Khamehchi, 2018). In addition, Shahsavari and Khamehchi noted that it is one of the MCDM methods that has been successfully applied in the oil and petroleum industry (Shahsavari & Khamehchi, 2018).

It has been used, for instance, to predict the best artificial lift method for well drilling (Alemi et al., 2011) and to determine the quality level of gas well drilling projects (Ahari & Niaki, 2014). Further, it has been applied in the field of decommissioning to a problem of land selection after mining (Martins et al., 2020a), in Enhanced oil recovery (EOR) selection (Shahsavari & Khamehchi, 2018) and in risk management assessments of construction projects (Russo & Camanho, 2015).

The main advantages of this method include, its ease of use, its logic that is rational and understandable, its robust reasoning that reflects the human choice path, the use of a scalar that considers best and worst alternatives simultaneously, and the simplicity of its mathematical process which are straightforward and can be easily programmed (Amiri, 2010; Dernis, 2019; Shih et al., 2007).

In addition, this method is considered “one of the most straightforward methods and it is suitable for a large scale problem comprising of large numbers of criteria and alternatives “ (Almulhim, 2014). According to Hwang and Yoon 1981, such advantages make TOPSIS a leading MCDA method compared to AHP and ELECTRE (Hwang & Yoon, 1981).

However, this method is based on human judgments that can be imprecise and this can make the modeling of the problems unrealistic (Almulhim, 2014). In addition, assigning weights and judging attributes may be challenging for decision makers (Martins et al., 2020a).

#### 5.4.3 The ELimination and Choice Translating REality (ELECTRE)

The ELECTRE (ELimination and Choice Translating Reality) model consists of an outranking method for solving a decision problem consisting of ranking a finite number of alternatives using the outranking relations. To evaluate these relations, the method uses concordance and discordance indicators. It was first presented by Benavoun, Roy, and Sussman in the 1960s as a method that can handle different types of problems, including selection, ranking, and sorting. (Almulhim, 2014; Greene et al., 2011).

Many versions of the ELECTRE have been developed since its conception by Roy and associates, including ELECTRE I, II, III, IV and TRI. It is important to note that these methods share the same fundamental principles with some differences that vary depending on the nature of the decision problem and its degree of complexity (Almulhim, 2014). Only the steps of the original version of the ELECTRE method are described here. For more details, please refer to (Ghosh et al., 2019) where several examples are presented.

**Step 1:** create the alternatives relative to the criteria quantity’s matrix  $X$  composed of  $m$  alternatives and  $n$  criteria. An element  $x_{ij}$  of this matrix refers to the measurement performance of the  $i$ th alternative according to the  $j$ th criterion.

**Step 2:** construct the normalized decision matrix using a normalization method, since the criteria in multi-criteria problems often have inconsistent and non-comparable dimensions. An element  $r_{ij}$  of the normalized decision matrix  $R$  is evaluated using the formula below (Eq1):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^m x_{ik}^2}}, \quad i=1, 2, \dots, m, \quad j=1, 2, \dots, n \quad \text{Equation (4)}$$

**Step 3:** construct the Weighted Normalized Matrix V. An element  $v_{ij}$  of this matrix is estimated as follows (Eq 2):

$$v_{ij} = w_j \cdot r_{ij} \quad \text{Equation (5)}$$

**Step 4:** determine the concordance and discordance sets used to rank the criteria of the different alternatives. The concordance set is composed of the set of criteria for which the alternative  $A_k$  dominates the alternative  $A_l$ . It is expressed as follows:

For profit criterion,

$$C_{kl} = \{j, v_{kj} \geq v_{lj}\}, \quad \text{for } j=1, 2, 3, \dots, n \quad \text{Equation (6)}$$

The second corresponds to the complementary subset and it is expressed as follows:

For profit criterion,

$$D_{kl} = \{j, v_{kj} \leq v_{lj}\}, \quad \text{for } j=1, 2, 3, \dots, n \quad \text{Equation (7)}$$

**Step 5:** construct the concordance and discordance matrices. These matrices are estimated using the concordance index, which represents the relative dominance of alternative  $A_k$  over alternative  $A_l$ . It is calculated by summing the weights of the criteria contained in the concordance set.

$$C_{kl} = \sum_{j \in C_{kl}} w_j \quad \text{Equation (8)}$$

The elements  $d_{kl}$  of the discordance matrix are defined as follows:

$$d_{kl} = \frac{\max_{j \in D_{kl}} |v_{kj} - v_{lj}|}{\max_j |v_{kj} - v_{lj}|} \quad \text{Equation (9)}$$

**Step 6:** determine the concordance and discordance dominance matrices. In this step, the threshold values of the concordance and discordance index are of major importance, since they are involved in the construction of these matrices. For the concordance dominance matrix F, an alternative  $A_l$  can only dominate another alternative  $A_k$  if its corresponding concordance index  $c_{kl}$  is higher than at least a certain threshold  $c$  value. Similarly for the discordance dominance matrix G which is defined by using a threshold value  $d$ .

**Step 7:** determine the aggregated dominant matrix which is calculated from the two previous matrices as follows:

$$e_{kl} = f_{kl} \times g_{kl} \quad \text{Equation (10)}$$

**Step 8:** eliminate the less favorable alternatives using the aggregate dominance matrix. Thus, the most favorable alternative is the one that dominates all other alternatives.

For real MCDM problems, the ELECTRE model is among the most important outranking methods employed (Hwang & Yoon, 1981). For instance, the energy sector has frequently used ELECTRE to support their decision making (Martins et al., 2020a). It has also been applied in the oil industry to assess the outranking relationships between alternatives. It has been applied, for example, to select artificial lift systems for well drilling (Alemi et al., 2011).

However, limited research exists on the application of TOPSIS and ELECTRE in the upstream oil and gas industry compared to the AHP/ ANP methods which have been widely applied in this type of context (Shafiee et al., 2019).

ELECTRE's strengths include its applicability even with incomplete information (Shafiee et al., 2019), and its results that are often relevant and realistic (Mammeri, 2017). In addition, Shahsavari and Khomehchi noted that it is one of the MCDM methods that has been successfully applied in the oil and petroleum industry (Shahsavari & Khomehchi, 2018).

However, its process and results can be difficult to explain for the decision-maker and require many parameters to set (Martins et al., 2020a). Moreover, according to (Ghosh et al., 2019), the most favorable alternative is in some cases difficult to identify. Another apparent weakness of these methods, is the incomplete ranking process that leads to a set of main alternatives (Triantaphyllou, 2000).

#### 5.4.4 The MR-Sort (Majority Rule Sorting) technique

Majority rule sorting (MR-Sort) is a simplified version of ELECTRE TRI (Sobrie et al., 2017). It aims to assign alternatives evaluated on multiple criteria to one of the predefined categories (Minoungou et al., 2021). Formally, let  $C = \{C_1, C_2, \dots, C_c\}$  be an ordered set of categories, from worst to best, to which the alternatives must be attributed. Thus, the best category is  $C_1$  and the worst category is  $C_c$ . Each category is associated with an upper and a lower limit profile, which are vectors of evaluations concerning all criteria. These limits profiles are used to “segment the evaluations scales into performance ranges appropriate for assignment into each category” (Cailloux et al., 2014).

Let  $P$  be a set of category profiles  $P = \{p_1, \dots, p_{c-1}\}$ . The assignment of an alternative to a given category is based on the comparison with these profiles for each of the evaluation criteria. Thus, two assignment rules are possible (Meyer & Olteanu, 2019). Under the pessimistic rule, an alternative is assigned to the highest possible category if it better than the lower limit of the category on most criteria. In contrast, under the optimistic rule, which is the most used in practice, an alternative is assigned to the lowest possible category if the upper limit of the category is better than this alternative on many criteria.

An alternative outperforms a limit profile if and only if the aggregate concordance, calculated using a weighted sum based on the weights of each criterion, is superior to a majority threshold  $\lambda$  fixed by the decision-maker. This indicator indicates the weight of a combination of criteria to be considered sufficient. Thus, by increasing the threshold level, the assignment model becomes more restrictive (Dernis, 2019).

The MR-SORT has been used in upstream oil and gas development projects for many purposes. For instance, it has been used as a decision support tool for selecting value-creation strategies for a project in host countries (Dernis, 2019) and for ranking contract strategy alternatives (Mammeri et al., 2017). The strength of this method is its ease of implementation compared to other methods, the fact that there are few decision parameters to define, and that the rule for assigning categories is relatively simple to understand. (Mammeri, 2017). However, selecting the limit profiles for the categories and the threshold are crucial and must be chosen carefully, otherwise the model may generate untrustworthy results.

## 5.5 Chapter conclusion: how to choose an adequate scenario selection method?

In the previous chapters 3 and 4, the first and the second steps of the proposed decision-making process are presented. After completing the second step, a set of plausible and relevant scenarios is proposed, but it is not clear which one is the best.

Through this chapter 5, the third step is presented which aims at solving the problem by selecting and recommending the best scenarios. The absolute evaluation methods, the complete comparison methods, and the comparison to reference point methods are introduced as possible methods to solve the problem.

The choice between these methods depends on the context of the project. Indeed, oil and gas projects are characterized by a diversity of contexts that requires the adaptation of analysis and evaluation methods.

To clarify the choice of which method to use, the main advantages and disadvantages of each of the MCDA methods discussed in this chapter are summarized in the Table 10 below. This table justifies the chosen methodology for solving the problem.

*Table 10: Strengths and weaknesses of the proposed solving methods*

Method	Strengths	Weaknesses
<b>Weighted Sum model (WSM)</b>	<p>Being easy to use and understand</p> <p>Using weights to differentiate the importance of each criterion.</p> <p>Transforming the raw data in a linear proportional way (Afshari et al., 2010).</p> <p>Involving simple calculations and not requiring complex computer programs (Martins et al., 2020a).</p>	<p>Allowing for trade-offs between criteria, so it is important to ensure that key criteria are not neglected (Martins et al., 2020a).</p> <p>Delivering results that do not always reflect reality because they may be illogical. (Martins et al., 2020a).</p>
<b>AHP</b>	<p>Integrating the quantitative and qualitative aspects of decision making makes this method effective and efficient in complex problems. (Vidal, 2009).</p> <p>Using a hierarchical structure that can easily be adapted to many complex problems. (Martins et al., 2020a).</p> <p>Being able to deal with multi-criteria decision making problems (Almulhim, 2014).</p> <p>Consideration of an unlimited number of criteria and sub-criteria (Ennaouri, 2010)</p>	<p>More compatible with individual decision making.</p> <p>Containing many pairwise comparisons (Martins et al., 2020a)</p> <p>Involving a high number of comparisons than the number of criteria (Ennaouri, 2010).</p> <p>Being susceptible to problems arising from the interdependence of criteria and alternatives.</p> <p>Requiring a deep mathematical understandings and knowledge (Sorooshian, 2015).</p> <p>Being used in many cases to calculate mainly the weighting of the criteria, while other techniques were preferred to evaluate the alternatives by TOPSIS or ELECTRE. (Russo &amp; Camanho, 2015).</p>

<p><b>ANP</b></p>	<p>Having a structure that is closer to reality because it makes it possible to model the interdependencies between the elements (De Jesus et al., 2019).</p> <p>Improving the transparency of the decision process (De Jesus et al., 2019).</p> <p>Being effective in solving problems in which there is dependence between criteria (Shafiee et al., 2019).</p>	<p>Failing to study the dependence between decision elements in MCDA problems under conditions of uncertainty (Almulhim, 2014).</p> <p>Failing to accurately reflect human preferences when the decision maker(s) cannot provide reliable data to assess the relationships between elements (Almulhim, 2014).</p>
<p><b>Pugh</b></p>	<p>Being easy to use, understand and implement as it does not require advanced mathematical knowledge.</p> <p>Being flexible as the user can easily add or remove alternatives or criteria without affecting the evaluation process (Ullman, 2006).</p> <p>Using a single score combining the evaluations, which allows decision makers to assess the relative value of each alternative separately (Ullman, 2006).</p> <p>Providing better information for the participants to decide which alternative to select (Pugh, 1981).</p>	<p>Being unable to handle missing information, as all alternatives must be evaluated against all criteria (Ullman, 2006).</p> <p>Discriminating criteria that cannot be traded off as the total evaluation is measured as a sum or weighted sum (Ullman, 2006).</p>
<p><b>TOPSIS</b></p>	<p>Having a logic that is rational and understandable and a robust reasoning that reflects the human choice path (Amiri, 2010; Dernis, 2019; Shih et al., 2007).</p> <p>Using a scalar that simultaneously considers the best and worst alternatives (Amiri, 2010; Dernis, 2019; Shih et al., 2007).</p> <p>Using a simple, straightforward and easily programmable mathematical process (Amiri, 2010; Dernis, 2019; Shih et al., 2007)</p> <p>Using this approach, a complete classification can be obtained, unlike the ELECTRE methods. (Triantaphyllou, 2000).</p> <p>Being effective in the field of petroleum engineering (Shahsavari &amp; Khomehchi, 2018).</p> <p>Being one of the simplest methods, and it is suitable for a large-scale problem with a large number of criteria and alternatives wang &amp; Yoon, 1981).</p> <p>Being an advanced MCDA method compared to AHP and ELECTRE (Hwang &amp; Yoon, 1981).</p>	<p>Relying on human judgments that may be inaccurate, which can make problem modeling unrealistic. (Almulhim, 2014).</p> <p>Assigning weights and judging attributes may be challenging for decision makers (Martins et al., 2020a).</p> <p>Providing results that may have significant variance, making it difficult to choose which method to use, TOPSIS or ELECTRE. (Zanakis et al., 1997).</p>

	<p>Being easier to use than the ELECTRE and TOPSIS methods (Santana, 1996).</p> <p>Maintaining the same number of steps regardless of the number of attributes (Martins et al., 2020a).</p>	
<b>ELECTRE</b>	<p>Being applicable even with incomplete information (Shafiee et al., 2019).</p> <p>Providing results that are often relevant and realistic (Mammeri, 2017).</p> <p>Taking into account the uncertainty and imprecision in the analyses (Martins et al., 2020a).</p>	<p>Having a process and results that can be difficult to explain to the decision-maker and require the definition of many parameters (Martins et al., 2020a).</p> <p>Encountering problems in some cases to identify the most favorable alternative (Ghosh et al., 2019).</p> <p>Providing incomplete ranking process that leads to a set of main alternatives (Triantaphyllou, 2000).</p>
<b>MR-SORT</b>	<p>Being simple to use and implement (Mammeri, 2017).</p> <p>Requiring few decision parameters to define (Mammeri, 2017).</p> <p>Having a relatively simple rule for assigning categories (Mammeri, 2017).</p>	<p>Selecting the limit profiles for the categories and the threshold are crucial and must be chosen carefully, otherwise the model may generate untrustworthy results.</p>

## 6 Chapter 6: An illustrative example

This chapter introduces an illustrative example of the proposed decision-making process. Due to the lack of interaction with the industrial interlocutors in the last phase of this Ph.D., we have had to propose a fictitious one.

## 6.1 Introducing the context and setting the methodological choices

The context of the fictitious example has been inspired by number of real past projects studied during the period of the Chair (2013-2021) for different reasons, like risk analysis, contractual strategy definition, in-country value strategy definition. With a lot of past discussions, notably with previous Ph.D. supervisors, we were able to propose a 14-decision scope ( $M = 14$ ). The following Table 1 summarizes these decisions.

*Table 11: List of decisions*

	Description of decision
D1	Select the development concept to be studied in the conceptual phase.
D2	Select the development concept to be studied in the pre-project phase.
D3	Select the number of wells to develop.
D4	Select the architecture of the wells to be developed.
D5	Select the contractual strategy.
D6	Select the strategies In-Country-Value (ICV)
D7	Select the data acquisitions to be performed.
D8	Select the drilling program.
D9	Select the best exploration and well evaluation scenario.
D10	Select the pipe network architecture
D11	Select the global assessment strategy.
D12	Select the means of execution.
D13	Select the logistics in terms of organization and means.
D14	Select the means of maintenance and inspection.

What is important here is to consider the methodological choices that are to be made as a vector which will be progressively built: (the modeling format, the optional network simplification, the problem formulation approach, the scenario generation approach, and the scenario selection approach). Except for the first one, methodological choices depend on previous ones, meaning that choosing for instance to not simplify a very complex network may prevent for using after a visual scenario construction strategy.

However, these choices cannot be made a priori before the network is built. The network complexity, i.e., the size and density of the network, is a criterion for selecting the modeling and displaying strategy. The more difficult it is to represent a graph without crossing links, the more it tends to choose the matrix format. This means that it is possible to build the network using one way and finally choosing the other way for the rest of the process.

The following section will thus introduce the model, then consider the choices.

6.2 Formulating the decision problem by selecting  $P$  decisions among  $N$

We introduce here the three steps for getting a specific multi-decision problem (corresponding to Chapter 6).

6.2.1 Modeling the global decision network

As discussed in chapter 3, the first step in the proposed multi-decision-making process is to model the global decision network. In this example, we first decided to display this network using a graph, which is shown in in the following Figure 50. The red links represent strength 2 or 3 interdependencies while the green ones represent strength 1 interdependencies. In other words, red links represent strong interactions and green links represent weak interactions.

As mentioned in 3.1.2, the interdependency assessment method was considered as an input since we were not able to know how the company would practically do this in its projects.

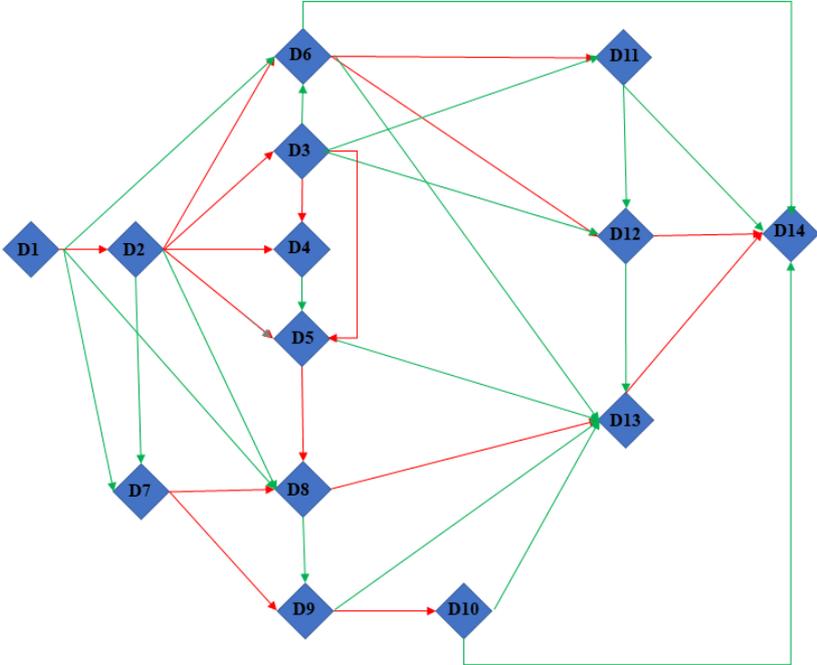


Figure 50: Global decision network

### 6.2.2 Simplifying or not the network?

Due to the high number of weak interactions, the sensitivity to their removal has been studied. It has thus been decided to use a simplified version of the network by removing edges of value 1.

The simplified decision network is shown in Figure 51. It consists of 14 nodes and 16 edges, respectively, decisions and average or strong relationships between pairs of decisions.

This decision network may be displayed and managed alternatively as a 14x14 matrix modeling the 16 possible interactions between its decisions (16 edges in the graph and 16 non-null cells in the matrix).

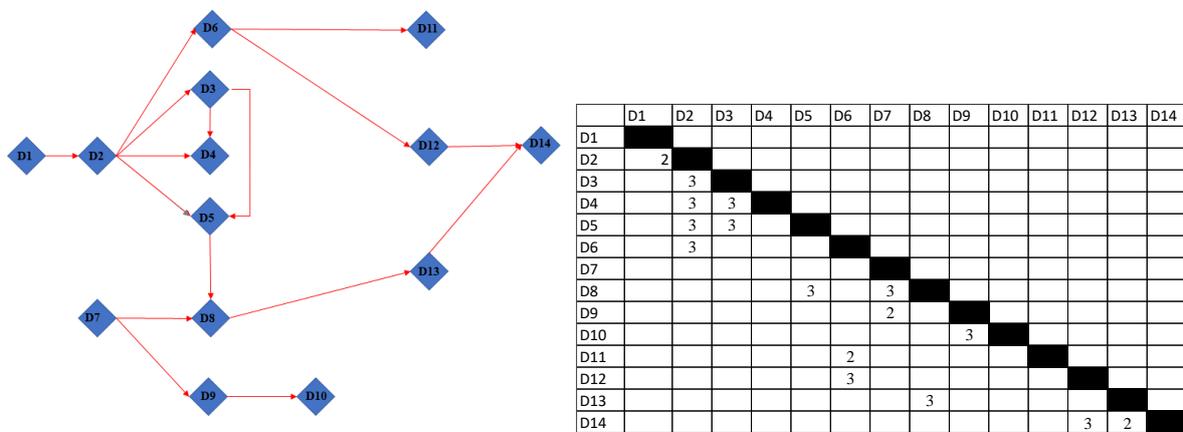


Figure 51: The simplified decision-decision graph and its adjacent matrix

We are in this example in a case of a network that has been built with a graph, with the decision to use the matrix format for the rest of the process due to its complexity.

### 6.2.3 Formulating the problem scope

To delimit the scope of the decision problem, it is necessary to first perform a pre-division of the network using the Top-down or the Bottom-up clustering approaches. The purpose of such a pre-division is to identify the packages of decisions, which are composed of strongly interdependent and temporally close decisions. This obviously also leads to the identification of isolated decisions that do not belong to any of the identified packages.

Since we are in the most likely situation of several decision-makers aiming at coordinating the decisions they own ( $P > 1$ ), we choose the top-down clustering approach.

For the example studied here, we have only one package of size 5. Once this package is built, the problem scoping strategy must be chosen. In our case, we have a package of five strongly interdependent decisions with the five being that temporally enough to follow a “5 among 5”-approach ( $P = N = 5$ ). In Figure 52, one can see the reshuffled matrix with the red square the sub-problem consisting of a package of five decisions, which must be made simultaneously.

	D2	D3	D4	D5	D6	D1	D7	D8	D9	D10	D11	D12	D13	D14
D2	■	■	■	■	■	2								
D3	3	■	■	■	■									
D4	3	3	■	■	■									
D5	3	3	■	■	■									
D6	3	■	■	■	■									
D1						■								
D7		Package 1					■							
D8				3			3	■						
D9							2		■					
D10									3	■				
D11					2						■			
D12					3							■		
D13								3					■	
D14												3	3	■

Figure 52: making 5 decisions among 5

Once the scope is defined, we now have to structure the problem to be able to generate several scenarios.

### 6.3 Structuring the problem and generating scenarios

As in Chapter 4, this section introduces the approach, based on initial modeling technique and decision-maker’s requirement, then presents how the chosen one, the QFD, is built. Finally, a heuristic is proposed to generate scenarios and pre-select relevant ones (at least non dominated).

#### 6.3.1 Building D-D and D-DA matrices for choosing the structuring approach

The four matrices introduced in previous Chapters are illustrated for our specific 5-decision package. Figure 53 illustrates the cross-decision matrix, which is an extract of the global decision network. The empty cells correspond to independent decisions. For instance, there is no relationship between the "contracting strategy" and the "In-country-value (ICV) strategy" decisions, and similarly for the “number of wells” decision and the “In-Country-Value (ICV) strategy”.

	<b>D1: development concept</b>	<b>D2: number of wells</b>	<b>D3: architecture of wells</b>	<b>D4: contractual strategy</b>	<b>D5: strategies In-Country-Value (ICV)</b>
<b>D1: development concept</b>					
<b>D2: number of wells</b>	x				
<b>D3: architecture of wells</b>	x	x			
<b>D4: contractual strategy</b>	x				
<b>D5: strategies In-Country-Value (ICV)</b>	x	x	x		x

Figure 53: Decisions x Decisions DSM

Figure 54 illustrates the second matrix, D-DA, where the first column corresponds to a development concept decision with three alternatives. The first alternative is to install the Liquefied Natural Gas (LNG) plant needed to purify and liquefy the gas in a cautionary bay and use a mix of offshore and onshore pipelines. The second is to install the LNG plant on site and the third to use only onshore pipelines. The second column concerns the number of wells with four alternatives while the third concerns their architecture. The fourth column represents a contracting strategy decision with four alternatives. The fifth column refers to the decision on strategies In-Country Value (LCV).

These strategies relate to industrial or non-industrial activities that a company must use or develop along its value chain when investing in a project in a host country. The goal of the proposed strategies is to contribute to local value in that country.

In our example, this gives a total number of 384 possible scenarios ( $3 \times 4 \times 2 \times 4 \times 4$ ). The shaded cells, shown in Figure 54, represent one configuration or scenario among the possible ones.

D2: Development concept	D3: Number of wells	D4: Architecture of wells	D5: Contractual strategy	D6: Strategies In-Country-Value (ICV)
Concept A: LNG plant at caution bay + mix offshore and onshore pipe	17 vertical wells	Fishbone well with 4 pairs of symmetric branches (branch angles 60)	CS1	Ensure access to water
Concept B: LNG plant on site	9 vertical wells	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS2	Power generation (creation of a domestic gas sector)
Concept C: onshore pipe only	9 horizontal wells		CS3	Construction of transport infrastructures
	15 horizontal wells		CS4	Creation of schools

Figure 54: Decisions x Decision Alternatives DMM.

At this point, once again, the most frequent situation encountered in our initial industrial context was the simultaneous consideration of compatibility and performance. That is why the QFD is chosen for structuring the multi-decision problem (the scenarios).

### 6.3.2 Building the DA-DA and PO-DA matrices for constructing the QFD

Figure 55 illustrates the third part of the QFD, corresponding to the Decision alternatives / Decision alternatives matrix. We used plausibility indices to evaluate to compatibility between pairs of alternatives (Im & Cho, 2013): the letter "P" marks a good match between the pairs or that the pair is optimal; the letter "K" designates that the pairs are possible, and could match, but not in an optimal way; the letter "X" indicates that pairs are incompatible.

To assign these indices, the participation of specialists in the field is necessary. The five blocks shaded in blue correspond to independent decisions. Three of them correspond to an empty cell in the D-D matrix in Figure 53. The remaining two blocks are basically interdependent, but in our case, given the nature of their alternatives, they are considered independent. The nature of the decision influences how to fill diagonal blocks. Some decisions are exclusive, which means choosing only one alternative per decision. For example, for the "number of wells" decision, only one alternative can be chosen, either 17 vertical wells, 9 vertical wells, 9 horizontal wells, or 15 horizontal wells. It is the same for the decision concerning the development concept.

Therefore, the diagonal blocks corresponding to these decisions are only filled with "-1", meaning that pairs of alternatives in such a block cannot be proposed together. However, for the decision related to the In-Country-Value strategies, a combination of alternatives is possible. It is possible to combine two alternatives: one action to provide access to water and another to create schools.

For the diagonal block corresponding to this decision, the compatibility between the different alternatives can be studied to determine whether they are compatible. Once these indices are assigned, consistent configurations can be identified and then evaluated at a later stage. At this point, a set of plausible scenarios, where each scenario is constructed by choosing one or two alternatives per decision that are compatible with each other, can be generated.

		Development concept			Number of wells				Architecture of wells		Contractual strategy				Strategies In-Country-Value (ICV)			
		Concept A	Concept B	Concept C	17 vertical wells	9 vertical wells	9 horizontal wells	15 horizontal wells	Fishbone well with 4 pairs of symmetric branches (branch angles 60)	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS1	CS2	CS3	CS4	Ensure access to water	Power generation (creation of a domestic gas sector)	Construction of transport infrastructures	Creation of schools
Development concept	Concept A	-1																
	Concept B	-1	-1															
	Concept C	-1	-1	-1														
Number of wells	17 vertical wells	-1	-1	-1														
	9 vertical wells	-1	-1	-1	-1													
	9 horizontal wells	1	1	1	-1	-1												
	15 horizontal wells	2	2	2	-1	-1	-1											
Architecture of wells	Fishbone well with 4 pairs of symmetric branches (branch angles 60)	-1	-1	-1	-1	-1	2	2										
	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	1	1	1	1	2	2	1	-1									
Contractual strategy	CS1	2	-1	2														
	CS2	2	1	1														
	CS3	1	-1	1														
	CS4	1	-1	1														
Strategies In-Country-Value (ICV)	Ensure access to water	1	-1	1														
	Power generation (creation of a domestic gas sector)	2	-1	2														
	Construction of transport infrastructures	2	1	2														
	Creation of schools	1	1	1														

Figure 55: Decision Alternatives x Decision Alternatives DSM

As for the last matrix corresponding to the Decision Alternatives cross the Projects Objectives DMM, the decisions alternatives are placed in columns and the projects objectives in rows.

Five categories of objectives are proposed for this matrix with guidance from industry collaborators. First is cost, then schedule, the third category is technical performances, the fourth is HSQE and the fifth is local content. Then, each category is divided into a set of sub-objectives. Once all the necessary elements are in place, the evaluation of the alternatives to the objectives can proceed. This evaluation is based on a comparison with a reference solution that is left to the discretion of the decision maker (Pugh, 1981).

However, it is important that the reference option be a known option and one that is generally considered to be very good. Thus, the evaluation principle is simple: if the considered alternative is better than the reference solution, we set 1. If it is worse than the reference solution, we set -1. If it is equal to the reference solution, 0 is set. For this matrix, it is important to be clear about the objectives of the project and careful about their evaluation.

			Development concept				Architecture and Number of wells			Architecture of wells		Contractual strategy				Strategies In-Country-Value (ICV)B								
			Solution de référence	Concept A: LNG plant at caution bay + mix offshore and onshore pipe	Concept B: LNG plant on site	Concept C: onshore pipe only	Solution de référence	17 vertical wells	9 vertical wells	9 horizontal wells	15 horizontal wells	Solution de référence	Fishbone well with 4 pairs of symmetric branches (branch angles 60)	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	Solution de référence	CS1	CS2	CS3	CS4	Solution de référence	Ensure access to water	Power generation (creation of a domestic gas sector)	Construction of transport infrastructures	Creation of schools
Objective	Sub-objective	Weight																						
Cost	Cost estimate	1	0	0	1	-1	0	0	-1	1	-1	0	1	0	0	-1	1	-1	0	0	1	-1	-1	0
	Cost vulnerability	1	0	0	-1	-1	0	?	?	?	?	?	?	?	0	-1	1	-1	-1	0	0	0	-1	-1
Schedule	Schedule estimate	1	0	0	-1	-1	0	0	0	0	0	0	1	1	0	1	-1	0	0	0	1	-1	-1	1
	Schedule vulnerability	1	0	0	-1	-1	0	?	?	?	?	?	?	?	0	-1	-1	-1	1	0	0	0	-1	-1
Technical objectives	Technical performance	1	0	0	0	0	-1	-1	0	0	0	1	0											
	Flexibility	1	0	0	-1	0	0	?	?	?	?	?	?	0	?	?	?	?	?					
	Complexity	1	0	0	-1	1	0	1	0	0	1	0	-1	-1	0	?	?	?	?	0	1	0	-1	1
HSQE	Environmental safety	1	0	0	-1	-1	0	-1	0	0	-1	0	1	1	0	?	?	?	?	0	1	0	0	1
	Personnel safety	1	0	0	-1	-1	0	?	?	?	?	?	?	?	0	?	?	?	?	0	0	0	0	0
	Societal value	1	0	0	-1	0									0	?	?	?	?	0	1	0	1	1
	Image of the company	1	0	0	-1	-1	0	?	?	?	?	?	?	?	0	?	?	?	?	0	1	0	1	0
Local content	Improve host country satisfaction	1	0	0	0	0	?	?	?	?	?	?	?	0	?	?	?	?	?	0	0	0	0	0
	Ability to handle the uncertain local work environment	1	0	0	-1	0	0	?	?	?	?	?	?	?	0	?	?	?	?	0	1	0	-1	1
Net score				0	-9	-6		-1	-2	1	-1		3	1		-2	0	-3	0		7	-4	-4	5
Rank				1	3	2		2	3	1	2		2	1		2	1	3	1		1	3	3	2

Figure 56: Project Objectives x Decision Alternatives DMM

### 6.3.3 Proposing scenarios alternatives based on the QFD

To facilitate the identification of plausible scenarios and estimate their features, we have implemented an algorithm dedicated to this purpose. It takes as parameter an Excel file containing the two following matrices: the compatibility matrix DA-DA and the performance matrix PO-DA. It permits to generate the plausible scenarios with their different scores, including the global compatibility score, the global performance score, and 4 other local performance scores detailed in Figure 57.

The global compatibility score is calculated to estimate the compatibility of each scenario. It is calculated by aggregating, for a given scenario, the plausibility parameters of each pair of its alternatives. The global performance score is calculated by aggregating the performance estimates for each alternative composing the given scenario.

The developed algorithm allowed us to derive 72 plausible scenarios from 288 possible scenarios. They are purposely left unsorted to avoid giving the impression that there is a preponderant criterion. Thus, the scenarios are listed only by number. For reasons of size, the above list represents only a portion of the complete list of all plausible scenarios.

As we can see in the following Figure 57, the difference between the global compatibility scores is not significant. Thus, the compatibility indices are comprised between 6 and 8. This means that in terms of compatibility, the scenarios are quite similar.

Plausible scenarios	Global compatibility of the scenario	Gobal performance of the scenario
S1 = {D1.1, D2.3, D3.2, D4.1, D5.1}	7	7
S2 = {D1.1, D2.3, D3.2, D4.1, D5.2}	8	-4
S3 = {D1.1, D2.3, D3.2, D4.1, D5.3}	8	-4
S4 = {D1.1, D2.3, D3.2, D4.1, D5.4}	7	5
S5 = {D1.1, D2.3, D3.2, D4.2, D5.1}	7	9
S6 = {D1.1, D2.3, D3.2, D4.2, D5.2}	8	-2
S7 = {D1.1, D2.3, D3.2, D4.2, D5.3}	8	-2
S8 = {D1.1, D2.3, D3.2, D4.2, D5.4}	7	7
S9 = {D1.1, D2.3, D3.2, D4.3, D5.1}	6	6
...	...	...
S33 = {D1.2, D2.3, D3.2, D4.2, D5.3}	6	-11
S34 = {D1.2, D2.3, D3.2, D4.2, D5.4}	6	-2
S35 = {D1.2, D2.3, D3.2, D4.4, D5.3}	6	-11
S36 = {D1.2, D2.3, D3.2, D4.4, D5.4}	6	-2
S37 = {D1.2, D2.4, D3.2, D4.2, D5.3}	6	-13
S38 = {D1.2, D2.4, D3.2, D4.2, D5.4}	6	-4
S39 = {D1.2, D2.4, D3.2, D4.4, D5.3}	6	-13
S40 = {D1.2, D2.4, D3.2, D4.4, D5.4}	6	-4
...	...	...
S58 = {D1.3, D2.4, D3.2, D4.1, D5.2}	8	-12
S59 = {D1.3, D2.4, D3.2, D4.1, D5.3}	8	-12
S60 = {D1.3, D2.4, D3.2, D4.1, D5.4}	7	-3
S68 = {D1.3, D2.4, D3.2, D4.3, D5.4}	6	-4
S69 = {D1.3, D2.4, D3.2, D4.4, D5.1}	6	1
S70 = {D1.3, D2.4, D3.2, D4.4, D5.2}	7	-10
S71 = {D1.3, D2.4, D3.2, D4.4, D5.3}	7	-10
S72 = {D1.3, D2.4, D3.2, D4.4, D5.4}	6	-1

Figure 57: Synthetic list of plausible scenarios

To facilitate the analysis, we have chosen to display the obtained outcomes in the form of a scatter diagram shown in Figure 57. This synthetic graph was created automatically by the same algorithm. Based on the diagram, we have chosen to classify the scenarios into 4 main categories, each of which is delimited by a specific-colored dotted line.

Concerning the scenarios delimited by the green dotted line, for a reference performance and compatibility that are equal to 0, a score of 7 in compatibility is obtained and an improvement in performance ranging from 2 to 7. Concerning the scenarios delimited by the orange dotted line on the left, they present the best compatibility score which is 8. However, to gain one more point in compatibility, the performance that was previously 7/10 must be violently degraded.

These scenarios have a negative performance score ranging from -2 to -12. Compatibility is thus improved by one point, but performance is significantly degraded compared to the scenarios located in the green zone. Given that the difference in performance is more significant than compatibility, this leads us to prioritize the performance criterion and consequently the category which is delimited by a green dotted line as well as all scenarios having positive performance scores.

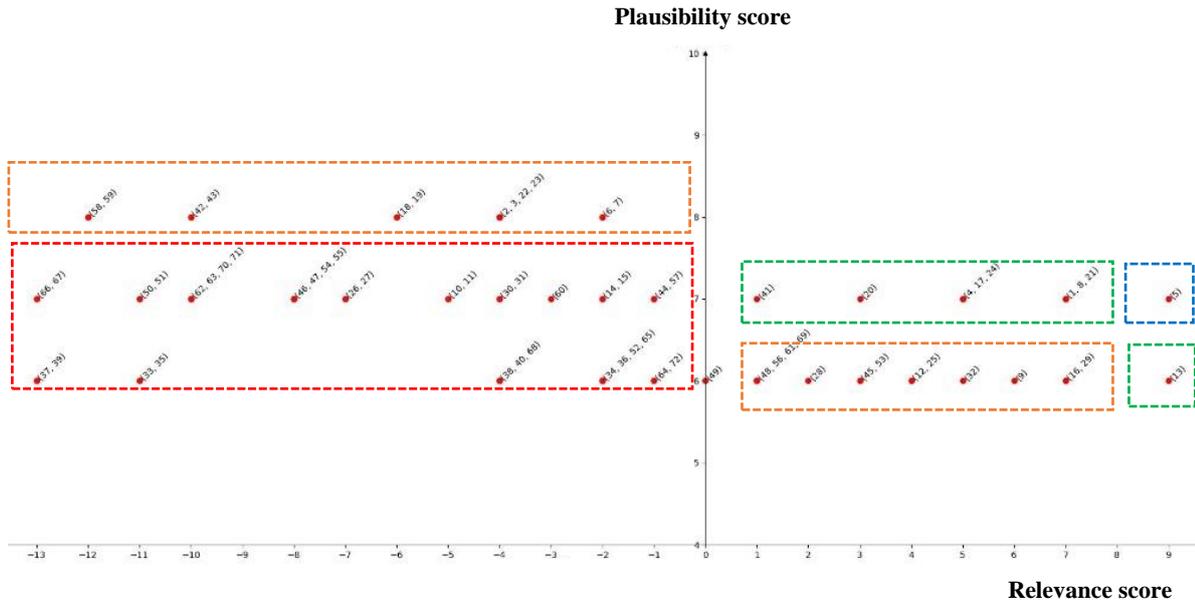


Figure 58: Plausibility-relevance diagram

Regarding the scenarios delimited by the orange dotted line on the right, which groups scenarios with a compatibility score of 6 and a performance score ranging from 1 to 7, they are dominated by the scenarios belonging to the green zone. For the scenarios delimited by a red dotted line, they are completely dominated. In summary, on the right side of the diagram, there is theoretically only one non-dominated solution which is delimited by a blue dotted line. The others are either strictly dominated or partially dominated with equality on one criterion and domination on another.

For example, scenario 13 delimited by a green dotted line has a maximum performance score but is dominated on compatibility by one point compared to scenario 5. On the contrary, the point regrouping scenarios 1, 8 and 29 has a maximum compatibility score but is dominated on performance by 2 points in comparison always with scenario 5.

Thus, scenario 5 is the preferred point, but we can also consider the other two points in case we are uncertain about certain evaluations. Therefore, we recommend considering the three points that correspond to scenarios 5, 13, and 1,8,21 (see Figure 59).

Recommended scenarios	Global compatibility of the tested scenario	Gobal performance of the tested scenario	Performance of objective 1 of the tested scenario	Performance of objective 2 of the tested scenario	Performance of objective 3 of the tested scenario	Performance of objective 4 of the tested scenario	Performance of objective 5 of the tested scenario
S1 = {D1.1, D2.3, D3.2, D4.1, D5.1}	7	7	0	2	0	4	1
S5 = {D1.1, D2.3, D3.2, D4.2, D5.1}	7	9	4	0	0	4	1
S8 = {D1.1, D2.3, D3.2, D4.2, D5.4}	7	7	3	0	0	3	1
S13 = {D1.1, D2.3, D3.2, D4.4, D5.1}	6	9	1	3	0	4	1
S21 = {D1.1, D2.4, D3.2, D4.2, D5.1}	7	7	2	0	1	3	1

Figure 59: Recommended plausible scenarios

More details about the alternatives chosen for each scenario are provided in Table 12.

Table 12: The chosen alternatives for each scenario

	<b>D1: development concept</b>	<b>D2: number of wells</b>	<b>D3: architecture of wells</b>	<b>D4: contractual strategy</b>	<b>D5: strategies In-Country-Value (ICV)</b>
<b>Scenario 1</b>	Concept A: LNG plant at caution bay + mix offshore and onshore pipe	9 horizontal wells	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS1	Ensure access to water
<b>Scenario 5</b>	Concept A: LNG plant at caution bay + mix offshore and onshore pipe	9 horizontal wells	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS2	Ensure access to water
<b>Scenario 8</b>	Concept A: LNG plant at caution bay + mix offshore and onshore pipe	9 horizontal wells	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS2	Creation of schools
<b>Scenario 13</b>	Concept A: LNG plant at caution bay + mix offshore and onshore pipe	9 horizontal wells	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS4	Ensure access to water
<b>Scenario 21</b>	Concept A: LNG plant at caution bay + mix offshore and onshore pipe	15 horizontal wells	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS2	Ensure access to water

#### 6.4 Evaluating and selecting among scenarios alternatives

In our context, which is a fictitious example based on real past projects, we consider the context that mostly inspired the example. This was an emerging country, new for the oil and gas operating company (the project leader), in a region of the world where the company has less mature contacts with potential contractors. This means that data are not so precise, excluding the absolute evaluation strategy.

Second, and it was the case in the real project, multiple scenarios were considered at the beginning of the project. The pairwise comparison of scenarios between one another would have taken too much time and energy, meaning that relative pairwise comparison strategy has been rejected. In the third possible strategy, a simple methodology had been preferred, for it is easier for operational decision-makers to use it. The final choice was MR-Sort, so we decided to use the same methodology in the fictitious example.

At this stage of the process, the five scenarios selected in the previous phase will be sorted using the MR-Sort method to select one scenario considering only the performance parameter, given that they are already plausible. This method requires the identification of a certain number of parameters. As shown in the following Figure 60, the performance vectors of the selected scenarios are introduced into the MR-Sort model, namely scenarios 1, 5, 8, 13, and 21. We also adopted the five categories of objectives used in the PO-DA matrix, namely cost, schedule, technical objectives, HSQE, and local content, including their relative weights.

We then defined two reference profiles, which are the lower reference point and the upper reference point. In order to simplify their identification for the decision makers, these profiles can be derived from the five selected scenarios. In this example, to avoid restricting the selection of scenarios, we decided not to use a demanding upper limit profile. We ruled in the same way for the elimination threshold ( $\lambda$ ) and set it at 0.67.

The principle of this method is based on the assignment of scenarios to one of four categories " Eliminated " (worse than the lower limit), "Better than the lower limit", "Between the two profiles", and "Better than the upper limit". This assignment is based on the comparison of each scenario against the two limit profiles.

	Weights (wi)	Lower reference point	Upper reference point	Elimination Threshold ( $\lambda$ )	Scenario 1	Scenario 5	Scenario 8	Scenario 13	Scenario 21
Cost	0.15	1	3	<b>0.67</b>	0	4	3	1	2
Schedule	0.15	1	2		2	0	0	3	0
Technical objectives	0.23	1	1		0	0	0	0	1
HSQE	0.31	1	3		4	4	3	4	3
Local content	0.15	1	1		1	1	1	1	1
1				Comparison to lower profile	0.00	0.15	0.15	0.15	0.15
					0.15	0.00	0.00	0.15	0.00
					0.00	0.00	0.00	0.00	0.23
					0.31	0.31	0.31	0.31	0.31
					0.15	0.15	0.15	0.15	0.15
				Sum of weights	0.62	0.62	0.62	0.77	0.85
				Category	Eliminated	Eliminated	Eliminated	Better than the lower limit	Better than the lower limit
				Comparison to the upper profile	0.00	0.15	0.15	0.00	0.00
					0.15	0.00	0.00	0.15	0.00
					0.00	0.00	0.00	0.00	0.23
					0.31	0.31	0.31	0.31	0.31
					0.15	0.15	0.15	0.15	0.15
				Sum of weights	0.62	0.62	0.62	0.62	0.69
				Category	Eliminated	Eliminated	Eliminated	Between the two profiles	Better than the upper limit

Figure 60: Sorting of scenario alternatives using the MR Sort model

The application of this method to the five selected scenarios allows us to retain the scenario 21 and to eliminate all the others. The detail of the retained scenario is presented in Figure 61.

As we can deduct from figure 38, the scenario 5 is the one that seems to be the most dominant, but it does not correspond to the one selected with the MR-Sort method. Indeed, on the scatter plot, each scenario has two scores. The relevance score is an aggregate score based on 4 criteria, allowing compensation between criteria, so that an advantage in one criterion can counterbalance a disadvantage in another. On the other hand, the MR-Sort method compares the scenarios to a boundary profile by considering the relative weight of each objective and the elimination threshold ( $\lambda$ ).

<b>Retained scenario</b>	<b>Development concept</b>	<b>Number of wells</b>	<b>Architecture of wells</b>	<b>Contractual strategy</b>	<b>Strategies In-Country-Value (ICV)</b>
<b>Scenario 21</b>	Concept A: LNG plant at caution bay + mix offshore and onshore pipe	15 horizontal wells	Radially distributed laterals with 3 pairs of symmetric branches (branch angles 60)	CS2	Ensure access to water

*Figure 61: Retained scenarios*

## 7 Chapter 7: Conclusions and Perspectives

In this chapter we will draw academic and industrial conclusions, as well as responses to the formulated research gaps and research questions. We then discuss the limitations of our research and suggest potential directions for future work.

## 7.1 Academic conclusions

We start by the academic part of this last Chapter, making conclusions on our proposals and how they respond or not to the formulated research gaps and research questions.

### 7.1.1 Wrap-up of the proposal and contributions

The main purpose of this Ph. D. thesis was to address the challenge of coordinating multiple interdependent decisions in the oil and gas context. **The high stakes in terms of cost, delay, quality, production, and HSE parameters have been introduced in Chapter 1.**

A global research question has been identified in Chapter 2, which is: **“How to support decision makers in making multiple decisions in a coordinated manner?”**. To address this issue in more detail, it was divided into two sub-questions: 1) “How to ensure that the interdependencies between decisions are properly managed?” 2) “How to support decision-makers in making multiple decisions in a coordinated manner and improving the compatibility of those decisions?”

To answer the main research question and the sub-research questions, a proposition has been introduced at the end of Chapter 2. **It consists of proposing a more adaptable and agile multi-decision-making process made of three blocks:**

- **Block #1: Modeling the decision network and formulating the multi-decision problem**
- **Block #2: Structuring the problem to propose relevant and plausible scenarios assembled from elementary decision alternatives**
- **Block #3: Solving the Problem by selecting and recommending scenarios**

Building the decision-making process is based on the context and multiple possibilities for each block. Indeed, given the diversity of oil and gas development project contexts, the proposed process is a multi-entry one. At each block, the decision-maker selects from a set of possible choices to adapt the decision-making process to the precise context.

In chapter 3 we have detailed the first block which consists of modeling the decision network and formulating the local decision-making problem. We have first expressed the need to build a global decision network that visualizes  $M$  decisions and the interdependencies they may have with other decisions. We argued then that graphs and matrices can be used to fulfill this need. Both methods allow to include all decisions and interdependencies of the decision network in one single model, each of them having its advantages and drawbacks, with a kind of complementarity. At this step of the process, the decision makers have the choice of using one of these approaches.

Then to formulate the local multi-decision problem, two interactions-based clustering approaches are proposed (the constraints of each approach can be adapted to the context of the study), with an additional sequential temporal regrouping of decisions. This allowed us to define the following two approaches: the top-down approach and the bottom-up approach. They both help to delineate the focus of decision makers on a specific set of  $N$  decisions, since considering the whole network of decisions at the same time is challenging and, in some instances, unfeasible.

The purpose of both approaches is thus to choose  $P$  decisions among  $N$  that will be outputs of the multi-decision-making process. Two parameters are considered in both approaches, which are interdependency between decisions and their temporal proximity. This means that the more interdependent decisions are, the more meaning there is in grouping them together. Similarly, the closer in time the decisions are, the more logical it is to group them together and make them synchronously.

For the Top-Down approach, from a set of  $M$  decisions, clusters of interdependent decisions are built to help determining the environment of  $N$  decisions that will be considered during the coordination process. Then, within a cluster of size  $N$ ,  $P$  decisions among  $N$  must be chosen using temporal clustering, so that they can be made simultaneously ( $P$  varying from 1 to  $N$ ).

As for the Bottom-up approach, the starting point is one single decision  $D_{i0}$  which the decision-makers are certain to consider. We identify then the  $P$  decisions which should be made simultaneously (including  $D_{i0}$ ) by studying the environment of  $D_{i0}$  on this two-axis diagram (interdependence strength and temporal proximity).

It is important to mention at this stage that both approaches allow to minimize difficulties of managing interdependencies and increase the ability to coordinate multiple interdependent decisions. The choice of the best approach belongs to the decision-makers, and it depends on several parameters such as: the ability to assess the interdependence between decisions, the availability of temporal data, the capacity of the team to manage several decisions at once, the number of decisions that can be comfortably managed by decision makers, the complexity of the network, the availability of historical data and feedback on projects, the level of importance of certain decisions, etc. Therefore, decision-makers must choose the appropriate way of construction according to their own criteria.

In chapter 4, we detailed the second block of the process which consists of structuring the information required to identify and assess decision alternatives, their contribution to project objectives (performance), and their interdependencies (compatibility). This is achieved by deriving relevant and plausible scenarios assembled from elementary decision alternatives. To do so, two matrix-based and one graph-based methods have been proposed. These methods offer the possibility to generate possible scenarios considering compatibility and performance criteria, either sequentially (morphological analysis), simultaneously (QFD), or with a hybrid way (graph exploration).

Another point to mention here is that these methods allow the scenario generation process to be carried out without bias or prejudice. Moreover, they prevent the selection of common scenarios that may not be relevant to the studied context. Indeed, generating plausible scenarios is important to avoid problems of inconsistency between decision alternatives. This leads in turn to less backtracking and iterations.

It also encourages further discussion and mitigates problems associated with a lack of transparency as well as traceability in the scenario development and selection process.

To facilitate the identification of plausible scenarios and estimate their features, a dedicated algorithm was built to address these issues. This tool was not originally planned, but during the illustration phase it appeared useful to automate the process of identifying plausible scenarios and estimating their characteristics (global compatibility score, global performance score, etc.). Indeed, this tool has proved its usefulness as it helped to save both time and effort.

An alternative is proposed in association with the graph-based exploration strategy, under the form of a lighter heuristic that can be applied on live during a decision meeting. At the end of this step a list of possible scenarios is obtained, with indicators of plausibility and relevance for each scenario.

In chapter 5, we detailed the third block of the process which consists of solving the decision-making problem. An evaluation and selection of recommended scenarios should be performed. We have proposed three families of MCDA methods as there is a need for an adequate scenario selection and recommendation technique. The first is absolute compensatory methods, the second is relative pairwise comparison methods, and the last is relative comparison to reference point methods. The decision-maker also has the choice here to use one of these strategies.

In chapter 6, a fictitious case study was constructed to test the validity of the proposed decision-making process, as we were unable to obtain a real case. This has certainly prevented us from advancing to the industrial implementation phase. The context of the fictitious example has been inspired by number of real past projects studied during the period of the Chair (2013-2021). We have applied the following methodological sequence: matrix-based approach, simplification, top-down scope definition, QFD-based structuring, MR-sort-based scenario selection.

As indicated in Chapter 2, two research gaps are framed the thesis. In the following paragraphs, we will show how they were addressed.

### 7.1.2 Focus on Research gap 1: the need to formalize interdependencies between decisions

For this research gap, the first block of the proposed decision-making process, which consists of modeling the decision network and formulating the local decision-making problem, takes into consideration the need to formalize interdependencies between decisions. This is achieved through **building a global, weighted, and oriented decision network**.

Graphs and matrices are two possible approaches dedicated to this purpose. They allow to model and analyze how decisions interact with each other, develop a deeper insight into the complexities of decision making, raise awareness of the interdependencies between decisions, and thus potentially mitigate their impact.

Through this block of the process, additional information is provided for decision-making in terms of understanding the interdependencies between decisions and their impacts allowing for more informed decision-making.

In the context of our case study, the findings demonstrate that decision network modeling provides enhanced value to the existing decision-making process and reduces project complexity by mastering better interdependencies between decisions and their impacts.

### 7.1.3 Focus on research gap 2: the need for coordination between interdependent decisions

Related to the second research gap, the proposed decision-making process permits to improve the coordination mechanisms between interdependent decisions thanks to different blocks. In the first block, building clusters of decisions using the Top-Down or the Bottom-up approaches offers many advantages. They avoid individual decision making, especially for the most interdependent decisions.

They allow to synchronize decisions, manage constraints simultaneously, and thus reduce conflicts and waste of time. The two approaches allow, therefore, a more coordinated multi-decision making. However, additional efforts to optimize decisions is required.

Once the decision cluster is constructed and the environment of the  $N$  decisions that will be considered during the coordination process is determined, it is possible to use a structuration method (QFD, morphological analysis, graph exploration) and a generation method (algorithm or heuristic) to construct plausible and relevant scenarios.

The scenarios generation process provided by such methods allow decision makers to coordinate multiple interdependent decisions in a structured and organized manner. They allow them to work in harmony and synchronize their interdependent decisions by construction. It seems impossible to finally recommend a scenario without any coordination.

## 7.2 Managerial implications

The proposed multi-decision-making process addressed three main industrial issues, which have been identified during the field survey conducting from the beginning of this Ph.D. thesis:

- A lack of formalization of interdependencies (implicit or vague knowledge)
- A lack of information about possible impacts of decisions
- A need for coordination strategies

Industrial supervisors underlined during the first half of the Ph.D. that such a process could improve coordination mechanisms between the major decisions of their projects. Even though decisions were interdependent, they were not often considered as such, and our proposed process permits (according to them) to have a better vision of the decisions to be made together and of the consequences of the choices.

However, some precise observations had been made. When talking about the two extreme scope definition strategies (1 among  $N$ , or  $N$  among  $N$ ), some actors found a priori that the synchronous strategy seemed more sophisticated and thus complicated to implement than the asynchronous strategy, as mentioned in (Figueiredo and Souza, 2012). This perception can be quite legitimate, since, considering the generic  $P$  among  $N$  strategy, it seems normal that the greater the  $P$ , the greater the coordination effort, which might be more complex and risky under certain project contexts (Yang et al., 2015).

It may also entail a radical change in their operational and organizational culture, which may be challenging to assimilate (Piwowar-Sulej, 2021). This is particularly true for those who are used to working alone in their office without interacting a lot with others.

But in the end, industrial supervisors and other industrial potential future decision-makers underlined that our process permitted to avoid individual decision-making processes and to promote the consideration of decisions made by other actors from other disciplines. This would (or could) potentially make a much more fluid and shared process in the end. However, all of this will require guidance and practice to be fully understood by all.

### 7.3 Limitations and perspectives

As with any process, we assert that the proposed multi decision-making process has limitations and there are still issues that need to be improved.

#### 7.3.1 Insufficient characterization of decisions alternatives

The first limitation is related to the characterization of the alternatives we consider during the decision-making process. Indeed, as suggested by (Delano et al., 2019), alternatives are one of the three major elements of any decision, and the best way to make better decisions is to find better alternatives”: considering insufficient alternatives and not ensuring sufficient evaluation of alternatives in the decision-making process can influence the quality of decisions in engineering design (Ullman 2001).

Two problems here can be identified. First, an insufficient identification of alternatives which might result in a poor decision-making process and in an unstable list of alternatives with new alternatives which need to be added over time. Second, even though they can be properly identified, alternatives might still be insufficiently evaluated (due to insufficient information about them or an unclear/unstable description of them which will results in an unclear/unstable evaluation of them).

Knowing these problems, we claim that identifying a solid list of alternatives is extremely important and as a perspective, we suggest that at least two improvements in our process can be proposed regarding these two issues:

**First, the list of alternatives of decisions used as input data for the QFD and the Morphological Analysis might be unstable.** This can directly cause a problem of incremental updating of alternative versions. Indeed, alternatives in the studied context are not necessarily well known at the beginning, but become so over time, and even if they are, they may be insufficiently stabilized. This implies that it is possible to face situations where, for example, the conceptual alternatives are known while the project alternatives are still undetermined. Therefore, in such cases, it might be difficult for instance to fully build up a complete matrix for the QFD or the Morphological Analysis, since alternatives might not be stabilized enough.

A perspective is thus to propose in the future additional steps in our process to develop, for instance, a QFD that builds up gradually as new information becomes available, with a precise description of the steps when the QFD must be reviewed for possible changes. Such steps will need to ensure that the structure of the QFD will be adapted to the addition of any new alternative, and that when adding such a new alternative, the evaluations related to this new alternative should be consistent with the evaluations between the already existing alternatives.

Sample pairwise comparisons are likely to be used as an evaluation check, while keeping the QFD construction process reasonable in terms of time. Another different perspective regarding this issue might be to anticipate the stability of the results over time when adding new alternatives or even new decisions: an approach based on a frequential analysis over the different results obtained when changing the set of decisions/alternatives (adding or deleting some) might be conducted in advance to ensure the robustness of the results initially proposed.

**Second, the evaluation of alternatives, even when properly identified, might be unclear/unstable.** In such a case, once again, it might be difficult here to fully build up a complete matrix for the QFD, since alternatives might not be stabilized enough in their characterization / evaluation.

A perspective here might be to extend our QFD approach with fuzzy numbers during the evaluation process. Using fuzzy numbers might indeed permit to handle, at least partially, the instability of the list of alternatives: if there are some changes in the characteristics of some alternatives, the result obtained with a fuzzy-numbered QFD might still be stable in the end (as long as the variation in the description of alternatives is not too important). The perspective of using fuzzy numbers in such an evaluation process appears to be promising since it has been widely used in several contexts (Liu, 2011), (Maritan, 2015), (Fitriana et al., 2019) and is therefore likely to be easier use than other sensitivity analyses approaches.

Still, we also suggest studying other improvements of QFD-based approaches integrating sensitivity analyses in the future, notably those based on linear regressions, gradient functions and optimization functions with convergence checks, like (Shabestari & Bender, 2017), to see if they could be applied to our context.

### 7.3.2 Defining the optimal moment when to make decisions

Originally, the objective of this Ph.D thesis was to develop a decision-making process that consider the notion of temporality of a decision. However, the optimal moment to make decisions remains a question that we could not address in this thesis, due to time constraints. Therefore, we simplified this issue by considering that the decision dates were simply inputs to the proposed multi-decision-making process. These decision dates are used in the first step of this process as input data to form the decision packages.

Nevertheless, it would be relevant to further study this question. Among the studies that addressed this question, we mention here the Ph.D. thesis conducted by Sissoko (2019). In order to identify the most favorable moment to take a decision, (Sissoko, 2019) proposed two functions. The first is a cost function which reflects the cost generated by the delay in the project in case of postponement of a decision. The second is a function which models the probability of having subsequent modifications likely to affect the considered decision. It is therefore necessary to make a trade-off between these two functions to get closer to the most favorable moment for the decision to be taken.

However, the proposed model does not propose a direct function to estimate the optimal date of decision. The two functions are used to compare the cost of the three proposed decision strategies and the one selected will be the one with the lowest expected cost. The three decision strategies or process decisions, as he called them, are as follows: the first is to integrate a possible alternative at the present time (A), the second is to analyze one or more alternatives simultaneously and wait for the results before choosing which one to integrate (B), and the third is to postpone the finalization of the problem to a later time and then decide either to integrate a given alternative or to conduct analyses to gather additional information (C).

We can also cite here the Ph.D thesis conducted by Marle (2002). To estimate the optimal moment to make a decision, an equation had been proposed based on the sequence of steps

involved in the lifecycle of an activity. If the decision date is earlier than the optimal date of the decision, then the risk is to make a decision while there was still time. If the decision date is higher than the optimal date of the decision, then the risk is to face some delay later.

However, both studies mentioned address the question of the appropriate moment to make a single decision. In our case, we intended to address this question for multiple decisions, rather than for a single decision, but we couldn't. Indeed, the question of the date will have to be asked several times, as in our context we deal with a N-decision network. This makes the question both more interesting and more complex. For this issue, we have not developed a proposal, but we are aware of the parameters to be considered, namely the risk of being very early and the risk of being too late.

The idea was to study the consequences that the date of a decision can have on the other decisions to which it is related. Thus, by varying the date of the decision in question, we not only vary the risks for this decision, but also for the others that are related to it.

### 7.3.3 An assistance to build the methodological sequence

The proposal presented in this research is a 3-block process with multiple choices at each step. What is interesting in such a multiple-choice approach is the diversity of possible methodological paths, depending on the context of the project. This was an initial requirement of the industrial client of this Ph.D. and leads to tens of possibilities. It should be mentioned that this proposition is highly dependent on the relationship and exchanges between practitioners in the field.

As we were not able to carry out iterations with the industrial interlocutors all along the Ph.D., this proposal could not be fully developed. In other words, the industrial feedback could have allowed us to build the methodological sequence adapted to each context based on the multiple possibilities for each block. We certainly would have been interested in developing this proposition, but it was difficult in terms of time to develop a process that would allow us to choose one option or another.

### 7.3.4 Two perspectives for practical implementation

As discussed in sub-section 4.4.4, an information system dedicated to the multi-decision coordination meetings could be developed. The difference between this information system and the algorithm developed and presented in section 4.3.4, is that the algorithm can be used to explore and then automatically display the list of plausible scenarios, while the information system could include additional features, such as testing and visualizing the consequences of selecting an alternative of a specific decision on the rest of the possible alternatives.

This information system can be a web application or a graphical tool that allows the decision makers to visualize, in real time, the feasible branches of alternatives and eliminate the implausible ones following the choice of an alternative. In other words, at each time the decision makers decide to set an alternative of a decision, this tool would consider this information and would display all opened and closed branches of alternatives.

As an example, let's imagine that in the first iteration, all possibilities are open and a choice is made for decision  $D_1$ , which consists in choosing between 3 alternatives. If  $D_{11}$  is chosen, then another view is obtained that removes all branches of alternatives and links that are related to  $D_{12}$  and  $D_{13}$ . In addition, since  $D_{11}$  is chosen, all branches that are not compatible with it are eliminated.

By using this tool, decision-makers could track the consequences of their choices and become aware of the constraints they add to the model. Indeed, in some cases, decision-makers may prioritize one alternative over another without considering the consequences of that choice. In that case, it may be useful to illustrate to these actors how the alternative they strongly desire can significantly reduce the degree of freedom of other decisions. This tool could therefore be used as a visual aid in a meeting to facilitate discussion and debate.

In terms of industrial application, we were unable to test the proposed process on a real case study in the context of oil and gas projects. So, an application in this or another field could of course be interesting as coordinating multiple decisions in complex environment is not limited to the oil and gas industry. A test on a real decision-decision network context can be, thus, conducted since in this Ph.D. we only presented a future assistance to network simplification.

## Appendix 1: Questionnaire developed during the interview phase

 <p><b>TOTAL</b> <b>LGi</b> L'Association Générale Industrielle</p>	<b>QUESTIONNAIRE DE THÈSE</b>	Questionnaire rempli par:
	<b>AIDE À LA COORDINATION DE DÉCISIONS MULTIPLES PRODUIT-PROJET : APPLICATION AUX PROJETS DE DÉVELOPPEMENT PÉTROLIERS ET GAZIERS DE TOTAL E&amp;P</b>	Entité:
		Fonction:
		Date:

Ce questionnaire comprend 6 catégories de questions, chacune comportant 3 questions ouvertes.

### 1. QUESTIONS GÉNÉRALES

- 1.1 Comment pourriez-vous décrire le processus décisionnel appliqué dans votre métier (Difficultés éprouvées lors de son application, degré de flexibilité, niveau de robustesse associé aux décisions prises, structure du pouvoir décisionnel, etc.) ?
- 1.2 Pensez-vous que tout choix devrait être formalisé en tant que décision dans un document officiel ? Ou encore que chaque décision devrait être documentée puis retracée, en termes d'alternatives non choisies et de justification de celle qui a été choisie ?
- 1.3 Pensez-vous que de nouveaux outils décisionnels sont nécessaires aujourd'hui afin de renforcer la robustesse de certaines décisions et envisager une meilleure qualité de la prise de décision ?

### 2. COMMENT SONT GÉRÉES LES INTERACTIONS ENTRE LES DÉCISIONS (COORDINATION D'ACTEURS) ?

- 2.1 Que pensez-vous de la façon dont les interactions potentielles entre les différentes décisions sont gérées et modélisées et celle dont la coordination entre les différents acteurs est assurée lors de la prise de décision ?
- 2.2 Est-ce que tous les liens de coordination entre les acteurs appartenant au même métier et à des différents métiers, ainsi que l'ensemble des liens d'interaction qui existent entre les différentes décisions prises à différents niveaux sont clairement définis dans les documents de travail ?
- 2.3 Comment pensez-vous pouvoir améliorer la manière dont les interactions potentielles entre les différentes décisions seront identifiées et évaluées ainsi que celle dont les acteurs se coordonneront entre eux ?

### 3. COMMENT SONT GERÉS LES IMPACTS QUE LES DÉCISIONS POURRAIENT AVOIR À L'AVENIR ?

- 3.1 Au moment de la prise d'une décision, étudiez-vous les impacts éventuels (directs ou indirects) que celle-ci pourrait avoir sur celles qui seront prises ultérieurement au sein de votre métier ou dans d'autres métiers, sur le degré de liberté de différents acteurs impliqués en aval et notamment sur leurs alternatives ?
- 3.2 Les documents de travail, vous permettent-ils de bien comprendre les impacts susceptibles de résulter de chacune de vos décisions prises ?
- 3.3 Comment pensez-vous que la gestion des impacts que les décisions sont susceptibles d'avoir à l'avenir pourrait être améliorée ? Et comment pensez-vous que nous puissions sensibiliser davantage les décideurs aux impacts qui peuvent résulter de leurs décisions ?

### 4. COMMENT EST GERÉE LA TEMPORALITÉ PAR RAPPORT À UNE DÉCISION ?

- 4.1 Avant de prendre une décision, considérez-vous le temps dont vous disposez pour préparer cette dernière et le temps nécessaire pour sa mise en œuvre par la suite ? Si oui, comment pouvez-vous les estimer et quels sont les facteurs qui peuvent les conditionner ?

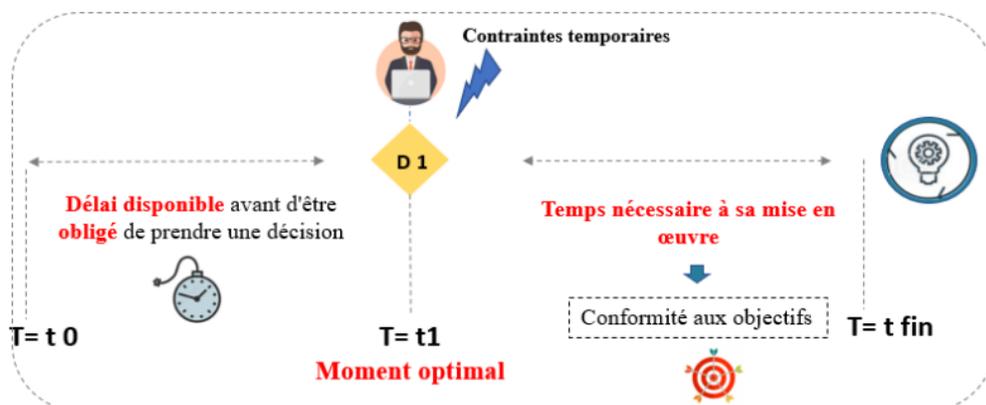


Figure 2 : Notion de temporalité associée à une décision

- 4.2 Le moment optimal pour prendre toute décision et le temps nécessaire à sa mise en œuvre sont-ils clairement documentés et justifiés dans les documents de travail ?
- 4.3 Que pensez-vous de la stratégie de décision au plus tard, qui consiste à laisser un certain nombre de scénarios ouverts le plus longtemps possible afin de disposer d'informations de plus en plus riches et précises jusqu'au moment où une décision est prise ?

## 5. COMMENT EST GERÉE L'INCERTITUDE PAR RAPPORT À UNE DÉCISION ?

5.1 Avant d'officialiser une décision à vos supérieurs ou à vos collègues de travail, évaluez-vous son degré de fermeté ? Si oui, comment pensez-vous que ce degré pourrait influencer les décisions qui seront prises plus tard, vos stratégies décisionnelles, vos relations avec vos collègues et avec ceux appartenant à d'autres métiers ?

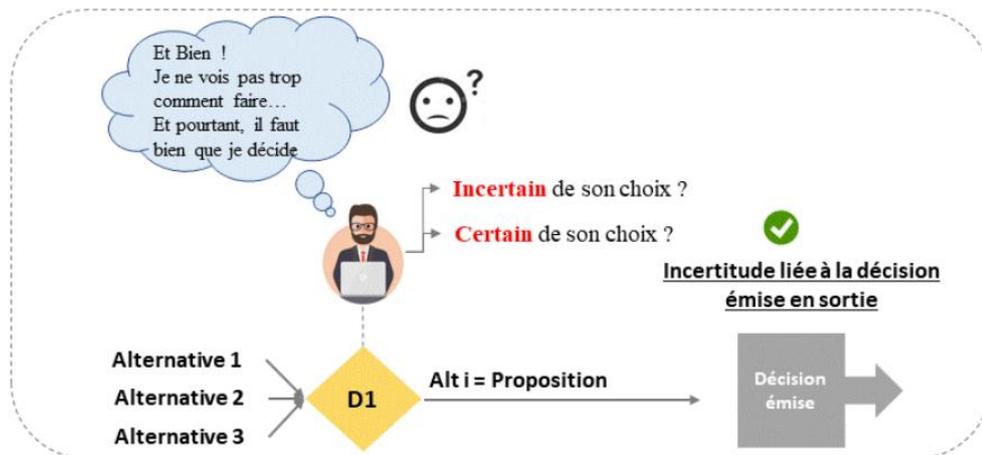


Figure 3 : notion d'incertitude associée à une décision

5.2 L'incertitude globale associée à chaque décision, y compris à celles prises ailleurs dans d'autres métiers, est-elle clairement renseignée dans les documents de travail ?

5.3 Selon vous, faudra-t-il améliorer la manière dont les incertitudes sont gérées et exploitées au cours des processus décisionnels ? Si oui, comment pensez-vous que cela puisse être fait ?

## 6. RISQUES DÉCOULANT DE DÉCISIONS DÉJÀ PRISES

6.1 Selon vous, quels sont les principaux risques et conséquences qui pourraient résulter d'une mauvaise coordination entre les acteurs, d'une méconnaissance de la notion de temporalité associée à vos décisions (prises de décisions trop tardives, prises de décision trop prématurées) ou encore d'un manque de certitude concernant certaines décisions voire un changement imprévu dans certaines décisions (retours en arrière) ?

6.2 Dans le cas où vous ne seriez pas en mesure de faire un choix parmi les alternatives proposées ou de définir le statut de certains points, que souhaiteriez-vous faire pour y parvenir ?

6.3 Assurez-vous le suivi et le contrôle des décisions prises ? (Mitigation des risques, valorisation des opportunités, etc.).

Le questionnaire est terminé.

Si vous avez des remarques concernant le questionnaire ou des précisions à apporter vous pouvez les inscrire ci-dessous.

Nous vous remercions pour le temps que vous avez consacré à compléter ce questionnaire

## Appendix 2: Extract from a description of the architects' activities, source (APP Hand BOOK)

Civit name	Civit description	Main links between activities
<b>Scope, schedule, and budget preparation stage</b>		
Initial identification of concepts	The Architect identifies an initial list of concepts based on work carried out during the preliminary study.	Predecessor(s): - Dev.Study KOM. Successor(s): - Final list of concepts. - Final list of concepts and preparation of the scope, schedule, and budget (for each discipline). - Selection criteria: list of rejected concepts.
Final list of concepts	The architect works with the GIS, FP, ECP, EXP, ICS, TA, and TEC disciplines to improve the initial list of concepts. A consolidation meeting is organized to establish a final list.	Predecessor(s): - Initial identification of concepts. Successor(s): - Distribution of concepts. - Preparation of the scope, schedule, and budget of the study with APP (for each discipline).
Distribution of concepts	...	
Drafting of the design bases	...	
Consolidation of scopes, schedules, and budgets	...	
<b>Review of concepts and selection criteria stage</b>		
Brief technical description and identification of critical elements	The Architect prepares a technical description of the identified concepts with the help of the study managers from the GIS, FP, ECP, EXP and ICS disciplines. For each concept s/he identifies the critical elements that could affect the choice of concepts. These elements form a list of issues to be addressed in the screening stage.	Predecessor(s): - Scope Schedule & Budget Review. Successor(s): - Drafting of the qualitative comparison grid and list of issues to be analyzed.
Drafting of the qualitative comparison grid and list of issues to be analyzed.	...	
<b>Screening phase</b>		
Consolidation and summary	The architect consolidates all the evaluations conducted by each discipline on the concepts selected in the previous stage. s/he summarizes this information by using the comparison grid to identify the concepts that will be analyze in greater detail during the study of selected concepts stage and justifies the concept rejections. The Architect prepares the QR Screening presentation material, which includes the list of assessed concepts, the differentiating criteria, and the justification for the rejections.	Predecessor(s): - Preliminary assessment of each concept (for GIS, ECP, ICS, EXP, PJC). - Specific studies of critical elements (for GIS, FP, ECP, ICS, EXP, LSO). - Preliminary CAPEX estimate (EST). - Preparation of benchmarks (EST). Successor(s): - QR Screening

Study of the selected concepts stage		
Update of BoDs	The purpose of this activity is to update the design bases after the QR Screening. The new design bases take into account the list of selected concepts. These are distributed to the disciplines.	Predecessor(s): - QR screening. Successor(s): - All activities in the study of selected concepts stage.
Uncertainties Final version	...	
Uncertainties consolidation meeting vF	...	
Consolidation of production & cost schedules	...	
Uncertainty and risk assessment	...	
Study finalization stage		
Dev.Study QR	<p>The Dev. Study QR meeting:</p> <ul style="list-style-type: none"> <li>- Ensures the quality of the study and the recommendations made, including the choice of the development concept.</li> <li>- Ensures that the development definition is mature enough to move on to pre-project phase.</li> <li>- Prepares the recommendations to be made to the ComAD.</li> </ul> <p>The Dev. Study QR must take place after all the study quality reviews have been completed and the economic calculations to be presented to the ComAD.</p> <p>The Dev.Study QR must take place after all the study quality reviews have been completed and the economic calculations have been made.</p>	<p>Predecessor(s):</p> <ul style="list-style-type: none"> <li>- Complete cost consolidation (EST).</li> <li>- GIS Review.</li> </ul> <p>Successor(s):</p> <ul style="list-style-type: none"> <li>- Post Dev. Study QR actions.</li> <li>- ComAD</li> </ul>
Post Dev.Study QR actions	...	
ComAD	The ComAD validates the reserves, the choice of development scheme and the development costs and schedules. It approves or blocks the transition to the next study phase.	<p>Predecessor(s):</p> <ul style="list-style-type: none"> <li>- GIS Review.</li> <li>- Dev.Study QR.</li> </ul> <p>Successor(s):</p> <ul style="list-style-type: none"> <li>- Study report.</li> </ul>
Study report	...	
Study coordination stage	...	

## Appendix 3: Conference paper presented in 2018 in the 21st edition of Lambda Mu Congress "Risk management and digital transformation: opportunities and threats"



21<sup>e</sup> Congrès de Maîtrise des Risques et Sécurité de Fonctionnement λμ21 Reims 16-18 octobre 2018

### ANALYSE DES SCENARIOS DE PROPAGATION DES RISQUES AU SEIN D'UNE ORGANISATION PROJET

#### ANALYSIS OF RISK PROPAGATION SCENARIOS WITHIN A PROJECT ORGANIZATION

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#### Résumé

Les projets complexes se caractérisent par un certain nombre de phénomènes, comme des réactions non-linéaires ou chaotiques, des chaînes de propagation et des boucles/cycles. Cela entraîne pour la maîtrise des risques de tels projets un double enjeu, qui est d'une part, de mieux comprendre et anticiper dans la complexité, d'autre part de décider en connaissant du mieux possible toutes les conséquences indirectes des alternatives de décisions.

Le projet étudié est un grand projet de construction, pour lequel une analyse de risques a été faite en 2014 et une autre en 2017. La problématique est la grande complexité du réseau de risques qui peut conduire le projet vers des phénomènes surprenants alors que l'analyse basique n'en tient pas du tout compte.

L'approche consiste en premier lieu à étudier de façon basique les risques projets, puis les scénarios de propagation à partir de la matrice d'interactions entre risques. A chaque fois, ces valeurs sont comparées aux valeurs 2017, pour essayer d'en tirer des réponses à deux questions :

- L'analyse avancée 2014 permet-elle de mieux anticiper ce qui va se passer en 2017 ? et si oui, est-ce général ou certaines zones particulières du projet, certains types de risques ?
- L'analyse avancée permet-elle de mieux choisir des actions à incorporer spécifiquement dans le Plan de Maîtrise des Risques ?

Certains développements sont encore en cours de réalisation, mais les premiers résultats montrent une amélioration significative de la capacité de prédiction dans les cas

#### Summary

Complex projects face some specific, nonlinear or chaotic phenomena, like propagation chains and loops/cycles. This implies for managing risks in such projects a double amount at stake: on the one hand, to better understand and anticipate consequences of complexity; on the other hand, to better decide by being aware of indirect consequences of decision alternatives.

We study here a big construction project, with two risk analyses made respectively in 2014 and 2017. The issue is the high level of complexity of the risk network of this project, that may involve some surprising phenomena, albeit the basic risk analysis does not take this complexity into account.

The approach consists first in analyzing risk with basic principles, then with advanced propagation-based principles, using the risk interaction matrix. For both analyses, a comparison is made with the actual 2017 values, in order to try to give answers to the following two questions:

- Does the advanced analysis in 2014 allow to better anticipate the actual status of 2017? And if so, is it a general improvement or is it specific to some areas of the project, to some types of risks ?
- Does the advanced analysis allow to better choose actions to put in the Risk Management Plan?

Some developments are still ongoing, however the first results show a significant improvement of prediction capacity in complex situations, where network density is high. Likewise, there is a significant difference in terms of treatment with the initial Risk Management Plan when considering complex nature of the risk network with the advanced analysis.

# Appendix 4: Conference paper Presented at the 21st International Dependency and structure modeling conference, DSM 2019

21<sup>st</sup> INTERNATIONAL DEPENDENCY AND STRUCTURE MODELING CONFERENCE,  
DSM 2019

MONTEREY, CA, USA, 23 – 25 September, 2019

## Robustness of Analysis of Simplified Networks

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**Abstract:** Networks are a common way to model systems, organizational systems that design these systems, and systems of systems that receive/benefit from these designed systems. They may contain hundreds or thousands of nodes and edges, which may decrease capacity to understand, analyze and make decisions. This paper tests the possibility to remove some elements in networks, mainly weak edges, in order to know if and how much precision is lost in terms of analysis. The results show that, first it is possible in some situations to make such a simplification, since the simplified network analysis is closer to the complete network analysis than the basic analysis, often made without network consideration. Second, this precision is still sensitive to the structure of the initial network and the position of weak links. Several tests on real past modeled networks are made to illustrate this research.

*Keywords:* networks, network-based analysis, graph simplification, robustness, analysis sensitivity

### 1. Introduction

Networks are a common way to model complex systems, organizational systems that design these systems, and systems (of systems) that receive/benefit from these designed systems. Projects have been recognized as complex since they are made of an organization that delivers a result for one or more recipients. It is usual since some decades to deal with project complexity using graph- or matrix-based model. DSM for instance is a technique that can be used to directly model project elements, like tasks (Eppinger et al. 1994), actors (Pollack, Costello, and Sankaran 2013), decisions (Jaber, Marle, and Jankovic 2015), deliverables (Jaber et al. 2017), or risks related to these elements, like in (Allan and Yin 2011; Borgonovo and Smith 2011; Fang, Marle, and Vidal 2010; Marle 2014; Marle and

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