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ABSTRACT

Welding of bends to manufacture bent pipes is a well-known method used worldwide. Cold bending is a competing manufacturing method and has its advantages and disadvantages.

The purpose of this thesis is to compare cold bending and welding of bends, both technically and economically. Analytic Hierarchy Process (AHP), requirements, standards and data from a reference project were used in the prioritizing between the manufacturing methods. During the study, several criteria were taken into consideration, and it was attempted to compare the different manufacturing methods as thorough as possible within the time given.

Requirements

Of the standards and requirements considered for the comparison, some differences between the two manufacturing methods appeared. Regarding NDT, the standards overall require more NDT for welding of bends than for cold bending. Note that generally there are written more requirements, information and limitations concerning welding in standards than about cold bending. It can be discussed if that favours cold bending or not.

Limitations

Cold bending as a manufacturing method to fabricate pipe bends has some limitations regarding pipe dimensions and bending radii. If there are lack of space (radii < 2D) and bigger pipe diameters (nominal pipe diameter > 8'') are needed, welding of bends is the preferred alternative.

Some are sceptic to use cold bending to manufacture bent pipes if the service is defined sour and/or low temperature systems. Tests have been conducted to qualify 6Mo and Duplex, Super-duplex cold bent pipes to be used in sour service conditions. Both tests passed with given partial pressure, and with no signs of sour service cracking (i.e., SSC/SCC) or corrosion. For low temperature service, cold bent Duplex materials are qualified down to -75^{o}C. Recommended use of Duplex materials is down to -50^{o}C. Low temperature Carbon steel pipes can't be bent as they lose their low temperature properties.

Economically

Analysis and calculations performed for this thesis show that cold bending has a significant lower cost and fabrication time per unit than welding, when post bend heat treatment is not required. The preferences change slightly when comparing with different types of material and pipe dimensions (pipe schedules, and nominal pipe diameters).

ACKNOWLEDGEMENT

This thesis is completed in the spring of 2021 at the University of Stavanger (UiS), Norway, to fulfil the Bachelor of Science and Technology.

As a soon to be mechanical engineer, I wanted to write about a subject with relevance for my future and education. I had a summer internship in Aker Solutions in the piping and layout department in the summer of 2020, where I briefly got introduced to an exciting and technological industry in constant development. During the last couple of months, I have learned a lot about the requirements, performance, advantages and disadvantages regarding the different techniques used to manufacture bent pipes, and I have still much to learn. Hence, this thesis is written with the thought to be understood by a reader with the same basic knowledge as I had when starting on this thesis. Thanks to Marius Gjære, and follow up by Camilla S. Melsom in Aker Solution for the opportunity and means to write about the subject presented in this thesis.

A special thanks to my supervisors for their time, support, and guidance:

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Kjetil Haaverstein at Aker Solutions for good and informative conversations online, and for his experience in the industry and answering my questionnaire.

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List of Abbreviations and Acronyms

ASME	The American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
EN	European Standard
HAZ	Heat Affected Zone
MDS	Material Data Sheet
MT	Magnetic Particle Testing
NDT	Non-Destructive Testing
NORSOK	The Norwegian shelf's competitive position
PCM	Pairwise Comparison Matrices
PMI	Positive Material Identification
PT	Penetrant Testing
PWHT	Post Weld Heat Treatment
RT	Radiographic Testing
SCC	Stress Corrosion Cracking
SSC	Sulfide Stress Cracking
UT	Ultrasonic Testing

1 INTRODUCTION

1.1 BACKGROUND

The oil and gas industry is an enormous industry where small changes can lead to significant impacts, especially economically. Only on the Norwegian continental shelf the production of oil liquids were around 2 million barrels per day in 2020, and Norway supplies about 2% of the global oil consumption (Norwegian petroleum, 2021). By always searching for new methods and new solutions, the industry can evolve and be more efficient, which can lead to more cost-effective solutions.

On platforms and processing plants, miles of pipes are constructed to transport fluids. Figure 1-1 illustrates the magnitude of pipes on a typical platform (Oljedirektoratet, 2020). By looking at this construction, one can see the scale of all the pipes in many different angles and positions. To construct a functioning pipe network like the one below, the pipes need to be re-routed in different directions and angles and carefully positioned to create the most efficient solution.

FIGURE 1-1: SLEIPNER A.

There are different methods on the marked used to route the pipes in new directions and angles. The most common methods are:

- Connect with an elbow
- Cold bending
- Induction bending

To connect the pipe with a pre-manufactured elbow is a well-known method used worldwide. The elbow can be manufactured with end connections to be welded, screwed or flanged. The techniques have evolved over the years, and by introducing new technology, the methods have improved. There are advantages and disadvantages with the different methods, some of them will be discussed in this thesis.

1.1.1 EXPERTS

The experts from Aker Solutions who were consulted for this thesis and the questionnaires for the AHP analysis, are shown in Table 1-1. The table also show their area of experience vs. years of experience.

TABLE 1-1: EXPERTS CONSULTED FOR THIS THESIS.

Name:	Discipline:	Years of experience:
Arild Hammer	Piping	31
Torstein Heggås	Piping	33
Kjetil Haaverstein	Piping engineering Valve engineer	14 12

1.2 AIM OF THE THESIS

The industry has a desire to compare the different manufacturing methods (cold bending and welding) used to produce bent pipes, both technically and cost-effectively.

1.3 THE SCOPE OF WORK

The scope in this thesis is to consider cold bending as an alternative to weld of bends in projects. Describing strengths and limitations (technically and cost-wise) with the different methods, and comparing requirements in standards and requirement specifications from the developer.

For cold bending, hydrogen sulfide (H_2S) in the medium can be a limitation for some materials. The requirements that must be set for knowledge about H_2S in the medium for relevant materials are described.

The main objectives, as defined by Aker Solutions are as follows:

- Consider cold bending as an alternative to welding of bends (technically and cost-wise).
- Compare requirements in standards using the two techniques (technically and documentation requirements).
- Compare in a project (Hod) where different methods are used.
- Compare requirements specification from the developer.
- Identify requirements for knowledge of H_2S in the medium for cold bending of pipes with different materials.

1.3.1 RESEARCH METHODS

During this thesis, the research methods has been mostly qualitative, but also some quantitative when comparing the different methods. Information have been gathered through literature search, interview with experts, search in standards and questionnaires in conjunction with the AHP analysis.

1.4 LIMITATIONS

- Time
- Requirements in standards, the most relevant requirements about the different manufacturing methods will be considered and included in the thesis.
- Due to limited time, the comparisons will be between cold bending and welding of bend, and not include induction bending.

2 WELDING PIPES

2.1 INTRODUCTION TO WELDING

Welding has a long history since it has been used in thousands of years to join metal pieces together. At the end of 19th century several new basic welding technologies evolved, mostly because it was possible to store and use gases as acetylene and oxygen and the possibility to use electricity (Weman, 2012).

The principal of welding is to use energy to join metals. Welding is often divided into two categories: pressure welding and fusion welding. In general, pressure welding uses mechanical pressure to join the metals. Fusion welding is described below using an illustration.

Figure 2-1: (a) is the initial prepared joint, (b) weld at the maximum temperature, also with joint filled with filler metal, (c) weld after solidification (Askeland et al., 2016, p.334). A filler material is often used (depending on the welding method), and it has approximately the same melting points as the base material. Heat affected zone (HAZ) is the area in the material that gets affected by the heat developing during welding. Meaning the area between the fusion zone (melted material) and the base material. Because of the heating and cooling the material changes its microstructure in HAZ. The changes depend, among other things, on the temperature (heat input), material, and time. In the HAZ, the material can be more brittle and harder than the original material depending on the content of the base material and cooling time after welding. Due to changes in microstructure HAZ is considered the weakest point, and the part is not stronger than the weakest spot.

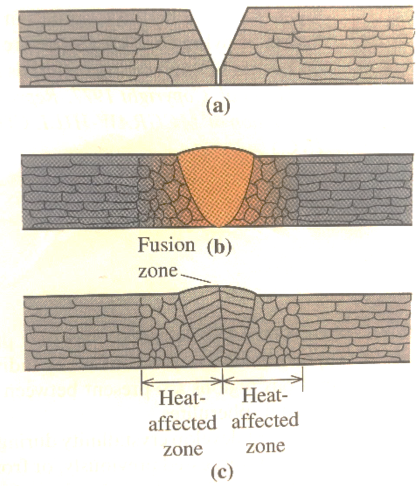

FIGURE 2-1: FUSION ZONE AND THE SOLIDIFICATION OF THE WELD.

Welding is often used to connect pipes together. A common method to manufacture a bent pipe is to weld an elbow to the pipe. Elbows are usually produced in standardized sizes, 45 and 90 degrees, but can also be ordered in customized angles. Ordering an elbow in a non-standardized size cost more than one in a standard size, therefore while constructing the pipe standardized elbows are mostly used.

Welding bends are time consuming. Firstly, a qualified welder is needed, secondly the welder must do the physical operation and finally, the weld need be quality tested. In addition, there are times where welds do not pass the quality tests, and errors can happen causing the need of weld repair.

2.2 Welding Requirements

2.2.1 Requirements according to NORSOK

NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations (Standards Norway, 2019). In accordance with NORSOK standard M-601, welding and inspection of piping, edition 6 (NORSOK, 2016):

NDT (non-destructive testing) requirements:

Requirements shown in table 2-1 and 2-2 (NORSOK, 2016, p. 19) applies for welded connections:

TABLE 2-1: DEFINITION OF NDT GROUPS.

NDT group	System service	PED fluid group	Pressure rating	Design temp. (°C)
1 [a b]	Non-flammable and non-toxic fluids only	2	Class 150 (PN 20)	-29 to 185
2	All systems except those in NDT Group 1	1 and 2	Class 150 and class 300 (PN 20 and PN 50)	All
3	All systems	1 and 2	Class 600 and above (≥ PN 100)	All

[a] Applicable to carbon steels and stainless steel type 316 only.
[b] Applicable for all materials in open drain systems.

TABLE 2-2: EXTENT OF NDT.

NDT group	Type of connection	Visual inspection, (%)	Volumetric testing, RT/UT, (%)	Surface testing, MT/PT, (%)
1	Butt weld	100	0	0
2	Butt weld	100	10	10
3	Butt weld	100	100	100

As seen from tables above, more NDT tests are required as the pressure rating classes increases.

Positive Material Identification (PMI), an NDT method to check the composition of alloy and material grade of piping systems on both base material and welds. The requirements state that PMI shall be performed to the following extent (NORSOK, 2016, p. 22):

- 100 % for systems in SS type 6MO, type 565 and type 22/25Cr duplex (duplex and super-duplex)
- 100 % for systems in austenitic steel and design temperature below -50^{o}C
- 10 % for systems in SS type 316

It should be mentioned that if corrosion testing is necessary then “welds in SS type 6Mo, type 565 and type 25Cr duplex shall be corrosion tested according to ASTM G 48, Method A” (NORSOK, 2016, p. 14).

2.2.2 REQUIREMENTS ACCORDING TO ASME

The American Society of Mechanical engineers (ASME) is the leading international developer of codes and standards associated with the art, science and practice of mechanical engineering (ASME, 2021). In accordance with ASME B31.3, process piping (ASME, 2018):

"Joints may be made by welding in any material for which it is possible to qualify welding procedures, welders, and welding operators in conformance with the rules in Chapter V" (ASME, 2018, p. 35).

Thickness requirements for straight section of pipe shall be determined in accordance with Eq. (1):

$$t_m = t + c \qquad (1)$$

c = sum of mechanical, corrosion and erosion allowances

t = pressure design thickness

t_m = minimum required thickness, including sum of mechanical, corrosion and erosion allowances

Post weld heat treatment (PWHT):

If PWHT is required, Table 2-3 shows the time and temperature needed (ASME, 2018, p 74), general notes, table with alternate PWHT (for some materials) and table with exemptions to mandatory PWHT can be found in ASME B31.3 p. 74-77. The different P-no. and group No. can be found in ASME BPVC section IX, QW/QB-420, as described in Table 2-3.

TABLE 2-3: HEAT TREATMENT.

P-No. and Group No. (ASME BPVC, Section IX, QW/QB-420)	Holding Temperature Range, °C (°F) [Note (1)]	Minimum Holding Time at Temperature for Control Thickness [Note (2)]	
		Up to 50 mm (2 in.)	Over 50 mm (2 in.)
P-No. 1, Group Nos. 1–3	595 to 650 (1,100 to 1,200)	1 h/25 mm (1 hr/in.); 15 min min.	2 hr plus 15 min for each additional 25 mm (in.) over 50 mm (2 in.)
P-No. 3, Group Nos. 1 and 2	595 to 650 (1,100 to 1,200)		
P-No. 4, Group Nos. 1 and 2	650 to 705 (1,200 to 1,300)		
P-No. 5A, Group No. 1	675 to 760 (1,250 to 1,400)		
P-No. 5B, Group No. 1	675 to 760 (1,250 to 1,400)		
P-No. 6, Group Nos. 1–3	760 to 800 (1,400 to 1,475)		
P-No. 7, Group Nos. 1 and 2 [Note (3)]	730 to 775 (1,350 to 1,425)		
P-No. 8, Group Nos. 1–4	PWHT not required unless required by WPS		
P-No. 9A, Group No. 1	595 to 650 (1,100 to 1,200)		
P-No. 9B, Group No. 1	595 to 650 (1,100 to 1,200)		
P-No. 10H, Group No. 1	PWHT not required unless required by WPS. If done, see Note (4).		
P-No. 10I, Group No. 1 [Note (3)]	730 to 815 (1,350 to 1,500)		
P-No. 11A	550 to 585 (1,025 to 1,085) [Note (5)]		
P-No. 15E, Group No. 1	705 to 775 (1,300 to 1,425) [Notes (6) and (7)]	1 h/25 mm (1 hr/in.); 30 min min.	1 h/25 mm (1 hr/in.) up to 125 mm (5 in.) plus 15 min for each additional 25 mm (in.) over 125 mm (5 in.)
P-No. 62	540 to 595 (1,000 to 1,100)	...	See Note (8)
All other materials	PWHT as required by WPS	In accordance with WPS	In accordance with WPS

3 COLD BENDING

3.1 INTRODUCTION TO COLD BENDING

During cold bending, mechanical force is used to form the pipes. The pipes can be bent in different radii. It is normal to refer the different radii as a number and the letter D, e.g., 3D. The letter D stands for the diameter of the pipe and the number in front for how much to multiply with the diameter. As seen in Figure 3-1 (ASME, 2018, p. 22) R_1 the centreline radius is determined from how large or small radii we want. Example, if we want a 3D bend, the centreline radius will be 3 times the diameter of the pipe. The number of degrees also needs to be specified, e.g., 45^o or 90^o bend.

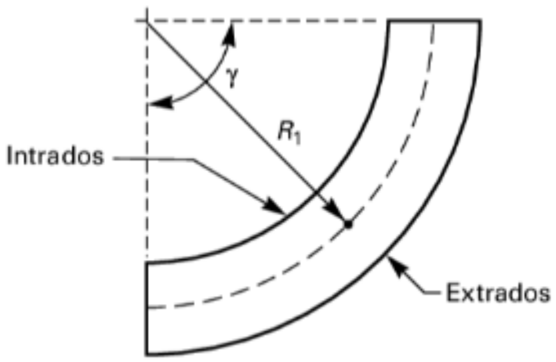

FIGURE 3-1: NOMENCLATURE FOR PIPE BENDS.

When using cold bending as a manufacturing method to produce bent pipes, the number of welds are reduced. So instead of welding an elbow between two straight pipes, it is bent in a bending machine. While bending, the mechanical properties can change. As seen in Figure 3-1 at the outside of the bend, at the extrados, the pipe will have tensile forces acting. Meanwhile at the inner side, at the intrados, compression forces act. On extrados it is important that wall thickness do not reduces too much and on intrados it is important with a smooth inner side and that not too much excess material takes place.

During the bending procedure, the operator must bend the pipe in a bigger angle than ordered. For example, if it is ordered a pipe bent in 90 degrees, the operator must bend it somewhere between 93-98 degrees according to Aker Solutions. This is due to the spring-back effect. How many degrees the operator has to bend it depends among others, type of material and thickness. The spring-back effect is caused by the elastic redistribution of the internal stresses after the removal of deforming forces (Chikalthankar et al., 2014). Because of the spring-back effect parts of the tension that is built up during the bending procedure is released after.

On the intrados side of the pipe inner wall wrinkles may occur. Wall wrinkles are not preferred. To minimize or prevent this deviation, operator can use a wiper die. Figure 3-2 from Aker Solutions illustrates a wiper die. Inner wrinkles are a result of excess materials on the inner side (intrados) when bending. The wiper die's function is to prevent the excess material moving forward, so the surface of the pipe remains smooth. Wiper die is mostly used when the pipes have relatively thin walls and smaller radii.

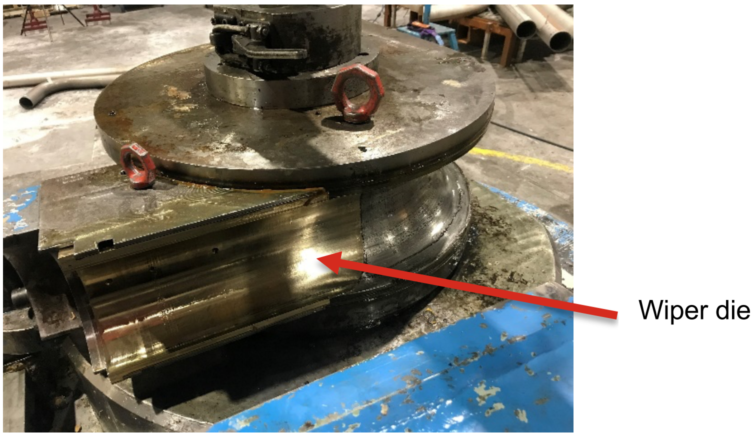

FIGURE 3-2: WIPER DIE.

To minimize wall thinning on extrados during the bending procedure, an external force can be applied. The tool used to apply the extra force is often referred to as a booster, shown in Figure 3-3 from Aker Solutions. As shown in Figure 3-3 the booster is in an open position. When in use, the booster will grip around the pipe and apply the extra force. The booster is placed upstream where the bending occurs, and by applying an extra force (push) towards the bend, the tension on the extrados can be reduced and wall thinning held at a minimum.

Often during the bending procedure, a mandrel is inserted into the pipe, shown as an example in Figure 3-3 from Aker Solutions. The purpose of this is to support the pipe from inside, and prevent the pipe from flattening, and in worst case collapsing.

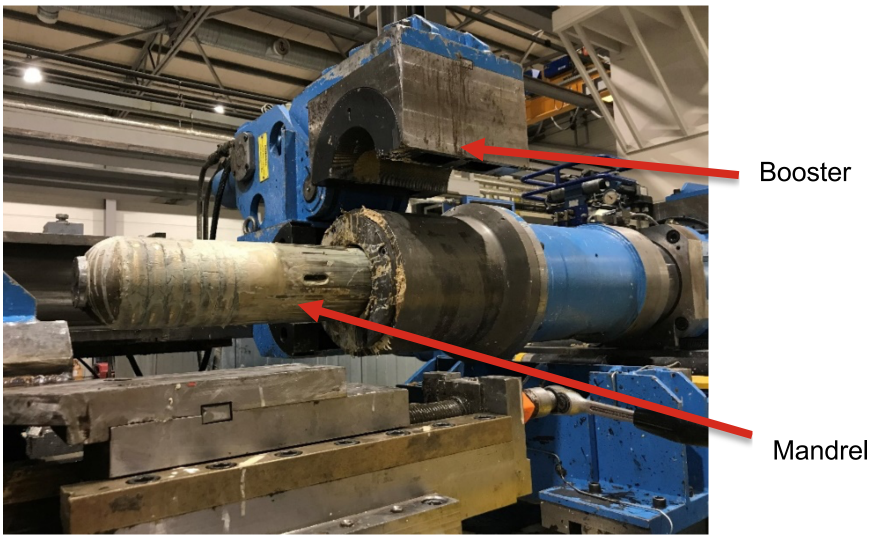

FIGURE 3-3: BOOSTER AND MANDREL.

While designing pipe systems, the designers have more flexibility if cold bending is used. This is because it is easier to choose a non-standardized angle for the bends. The designer can choose an angle on the pipe up to 180º. However, the are some limitations. One of them is that the minimum acceptable radii for cold bending according to Aker Solutions, is 2D. So, if the designer is designing a piping system and has lack of space, cold bending cannot be used if the radii needed is smaller than 2D. Also, the pipe must be a bit longer when bending to compensate for the bend, therefore the price will increase a bit to buy a longer pipe. Spreads the purchase of standard elbows, which is more expensive than extra pipe length.

There are some limitations in conjunction with pipe sizes. In Aker Solutions the maximum nominal pipe diameter for cold bending is 8’’, to comply with applicable regulations.

3.2 COLD BENDING REQUIREMENTS

3.2.1 REQUIREMENTS ACCORDING TO NORSOK

In accordance with NORSOK M-630, material data sheets and element data sheets for piping, EDS NBE1 (NORSOK, 2020) for cold bending of pipes:

Qualification:

- The qualification bend shall be 90^o
- Samples for destructive testing shall be taken from the extrados area

"Acceptance criteria shall be according to the applicable MDS with the following exceptions:"

- Elongation shall be > 14 %
- The minimum absorbed impact energy shall be 27 J average and 20 J single
- The hardness of any cold-formed material shall not exceed the limits specified in Table 3-1 (NORSOK, 2020, p. 193)
- For items exposed to H_2S-containing service shall comply with ISO 15156

TABLE 3-1: LIMITATIONS AND SPECIAL REQUIREMENTS FOR COLD BENT PIPES.

Material	Service	Limitations and/or additional requirements
CMn-steel MDS C31/C31S, C32/C32S, C41/C41S, C42/C42S, C51/C51S, CH61S	Utility service and non-sour hydro-carbon service	The maximum hardness shall not exceed 350 Hv10 or 35 HRC. When the hardness exceeds this limit a post bend heat treatment according to ASME B31.3 shall be applied.
	H_2S containing service defined sour in accordance with ISO 15156-2.	Not acceptable to use without post bend heat treatment unless qualification testing in compliance with ISO 15156 is successfully qualified and documented, ref. item 5.
Type 316, MDS S11, S12	Utility service and non-sour hydro-carbon service	
	H_2S containing service within the limitations of ISO 15156-3.	The maximum hardness requirements shall be 22 HRC and SSC testing to ISO 15156 is required.
Type 22Cr and 25Cr duplex, MDS D41, D42, D48, D51, D52, D58, DH41, DH42, DH48, DH51, DH52 and DH58.	Utility service and non-sour hydro-carbon service	
	H_2S-containing service within the limitations of ISO 15156-3.	Not acceptable to use without post bend heat treatment unless qualification testing in compliance with ISO 15156 is successfully qualified and documented, ref. item 5.
	Subsea	The maximum hardness of any cold bend part shall not exceed 350 Hv10 or 35 HRC
SS Type 6Mo MDS R11, R12 and R18	Utility service and non-sour hydro-carbon service	
	H_2S containing service within the limitations of ISO 15156-3.	The maximum hardness shall be 328 HB or 35 HRC and SSC testing to ISO 15156 is required.
Titanium Grade 2, MDS T21, T22	Utility service	
	H_2S containing service within the limitations of ISO 15156-3.	Not acceptable unless specifically qualified according to ISO 15156, ref. Item 5.

NDT:

- 100% visual inspection
- 10% surface testing, by the MT and PT methods (for carbon steel and stainless-steel grades, respectively)

3.2.2 REQUIREMENTS ACCORDING TO ASME

In accordance with ASME B31.3, process piping (ASME, 2018):

The minimum required thickness, t_m , of a bend after bending, in its finished form, shall be determined in accordance with Eq. (1) and Eq. (2) (ASME, 2018, p. 19-22):

The required thickness of straight sections of pipe:

$$t = \frac{PD}{2[(\frac{SEW}{I})+PY]} \qquad (2)$$

Intrados:

$$I = \frac{4\left(\frac{R_1}{D}\right)-1}{4\left(\frac{R_1}{D}\right)-2} \qquad (3)$$

Extrados:

$$I = \frac{4\left(\frac{R_1}{D}\right)+1}{4\left(\frac{R_1}{D}\right)+2} \qquad (4)$$

t = pressure design thickness

t_m = minimum required thickness, including sum of mechanical, corrosion and erosion allowances

d = inside diameter of pipe

D = outside diameter of pipe

E = quality factor (from Table A-1A or Table A-1B in ASME B31.3)

P = internal design gage pressure

S = stress value for material (from Table A-1 or A-1M in ASME B31.3)

W = weld joint strength reduction factor (from ASME B31.3)

Y = coefficient (from Table 304.1.1 in ASME B31.3)

R_1 = bend radius

Bend flattening:

- The difference between maximum and minimum diameters at any cross section shall not exceed 8% of nominal outside diameter for internal pressure and 3% for external pressure.

Bending temperature:

- During cold bending of ferritic materials, the temperature shall be kept below the transformation range. It is normal to perform the cold bending procedure at room temperature.

Required heat treatment:

Heat treatment after cold bending is required for:

- P-Nos. 1-6 materials, where the maximum calculated fiber elongation exceeds 50% of specified basic minimum elongation for the applicable specification, grade and thickness. This may be waived if it can be demonstrated that in the finished condition, the most severely strained material retains at least 10% elongation.
- Any material requiring impact testing, where the maximum calculated fiber elongation after bending/forming will exceed 5%
- Specified in the engineering design

The different P-no. and group No. can be found in ASME BPVC section IX, QW/QB-420, as described in Table 2-3.

If heat treatment after cold bending is required, Table 2-3 (p. 6) show the temperature and time needed.

3.2.3 REQUIREMENTS ACCORDING TO EUROPEAN STANDARD (EN)

According to NORSOK "the out-of-roundness and waves at bends tolerances shall comply with EN 13480-4" (NORSOK, 2020, p. 195).

In accordance with NS-EN 13480-4 – Metallic industrial piping - Part 4: Fabrication and installation (European Standard, 2017):

Tolerances concerning out-of-roundness of bends:

Under internal pressure equal to, or greater than, the external pressure (European Standard, 2017, p. 17):

$$\mathbf{u} = \frac{2(\mathbf{d_{o\,max}} - \mathbf{d_{o\,min}})}{(\mathbf{d_{o\,max}} + \mathbf{d_{o\,min}}}\mathbf{100} \qquad (5)$$

u = out-of-roundness (in %)

$d_{o\,max}$ = is the maximum outside diameter (in mm)

$d_{o\,min}$ = is the minimum outside diameter at the same cross section as $d_{o\,max}$ (in mm)

Under external pressure and vacuum (European Standard, 2017, p. 18):

- "Values for out-of-roundness shall conform to the values stated in the design".

Tolerances concerning waves at bends:

Waves at bends are acceptable as long as they comply with both of the following conditions: (European Standard, 2017, p. 18-19)

a)

$$\boldsymbol{h_m} \leq \mathbf{0,03}_{\boldsymbol{d_{01}}} \qquad (6)$$

$$\boldsymbol{h_m} = \frac{\boldsymbol{d_{02}} + \boldsymbol{d_{04}}}{\mathbf{2}} - \boldsymbol{d_{03}} \qquad (7)$$

h_m = mean height of adjacent waves (formula (7))

d_{01}, d_{02}, d_{03} and d_{04} is shown in Figure 3-4 from EN 13480-4 (European Standard, 2017) b)

$$a \geq 12 * h_m \qquad (8)$$

a = wave distance

h_m = shown in formula (7)

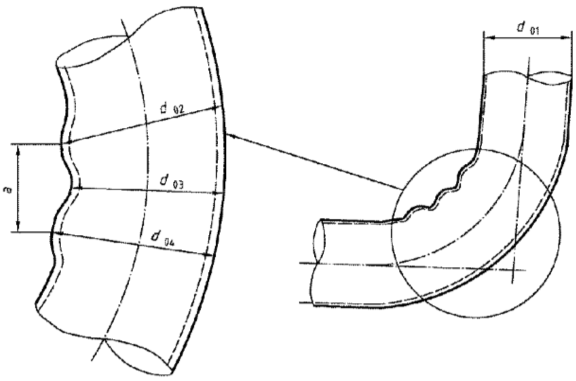

FIGURE 3-4: PIPE WAVE HEIGHT.

3.2.4 Additional Requirements from Developer

In accordance with ASTM B861/B862 the requirement for Titanium grade 2 is minimum 20% elongation on a 2 in. or 50 mm gauge length specimen (ASTM, 2019a),(ASTM, 2019b), while the requirement from the developer is ≥ 25%.

4 HYDROGEN SULFIDE (H_2S)

4.1 INTRODUCTION TO H_2S

Hydrogen sulfide (H_2S) is a colourless, poisonous, flammable gas that smells like rotten eggs (Markali, 2019). In small concentrations it smells the distinctive smell, but in bigger concentrations the sense of smell is paralyzed.

H_2S can cause corrosion in equipment and pipes on platforms and processing plants. When the limits of H_2S is above a certain threshold in a stream of oil and gas, the service is defined sour.

4.2 H_2S REQUIREMENTS

Tests according to ISO 15156 have been performed for Kværner (merged with Aker Solutions in 2020) to qualify cold bent pipes with different materials to be used in sour service conditions. Both tests passed with given partial pressure, and with no signs of sour service cracking (i.e., SSC/SCC) or corrosion. The materials were approved with following partial pressure:

- P_{H2S}: 1000 mbara (= 1.0 bara) for 6Mo pipes (ref. Appendix B)
- P_{H2S}: 100 mbara (=0.1 bara) for 22% Cr duplex and 25 % Cr super duplex stainless steel (ref. Appendix A)

If service is defined sour in accordance with ISO 15156, then following requirements for different cold bent pipe materials (NORSOK, 2020, p. 193) applies (also shown in Table 3-1):

CMn-steel:

Not acceptable to use without post bend heat treatment unless qualification testing in compliance with ISO 15156 is successfully qualified and documented.

Type 316:

The maximum hardness requirements shall be 22 HRC and sulfide stress cracking (SSC) testing to ISO 15156 is required.

Type 22Cr and 25Cr duplex:

Not acceptable to use without post bend heat treatment unless qualification testing in compliance with ISO 15156 is successfully qualified and documented.

SS Type 6Mo:

The maximum hardness shall be 328 HB or 35 HRC and SSC testing to ISO 15156 is required.

Titanium Grade 2:

Not acceptable unless specifically qualified according to ISO 15156.

5 REFERENCE PROJECT

5.1 HOD

Hod is a field in the southern part of the Norwegian sector in the North Sea, about 13 kilometres south of the Valhall field. The water depth is 72 meters. Hod was first found in 1974 and the production started in 1990. The platform "Hod" is an unmanned wellhead platform unit that is remotely controlled from Valhall. Facts and Figure 5-1 about Hod from the Norwegian Petroleum Directorate (Oljedirektoratet).

The production from this unit is currently stopped, but in December 2020 a plan for rebuilding was approved by the Norwegian Ministry of Petroleum and Energy.

FIGURE 5-1: HOD.

The new Hod, named Hod B will copy the concept, execution model and organization from Valhall Flanke Vest, which started production in December 2019 (Aker BP, 2020). The first oil from Hod B is planned in the first quarter of 2022. Hod B will receive power from shore thru Valhall. Parts of the platform is currently being built at Aker Solutions in Verdal.

Aker BP is the operator and has 90 percent owner interest, while Pandion Energy is partner with 10 percent interest (Aker BP, 2020).

The reservoir connected to Hod lies on 2700 meters depth (Oljedirektoratet), and the oil and gas is produced with pressure depletion. Further the oil and gas is transported by pipeline to Valhall field for processing, before oil and natural gas liquids (NGL) is transported to Ekofisk field centre and gas is sent via Norpipe to Emden in Germany (Oljedirektoratet).

5.2 Data from Reference project

A survey was conducted to compare cold bending and welding of bends on the platform Hod. Data was collected from most of the systems where both manufacture methods (cold bending and welding of bends) are suitable, this data were used for the calculations performed in this chapter (Material cost data, 2020). The data were averaged using arithmetic mean, as shown in Eq. (9):

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i \qquad (9)$$

5.2.1 Fabrication time

To compare the manufacturing methods in relation to fabrication time, the data were divided into material groups and nominal pipe diameter. When manufacturing bent pipes there are some differences in fabrication time of pipes with different pressure ratings in the same nominal pipe diameter group. For instance, it takes more fabrication time to manufacture a bent pipe in pipe class 150# than in 1500#, for both manufacturing methods. Therefore, for simplicity the comparison between them will be in the different nominal pipe dimensions, as shown in Figure 5-2, Figure 5-3 and Figure 5-4:

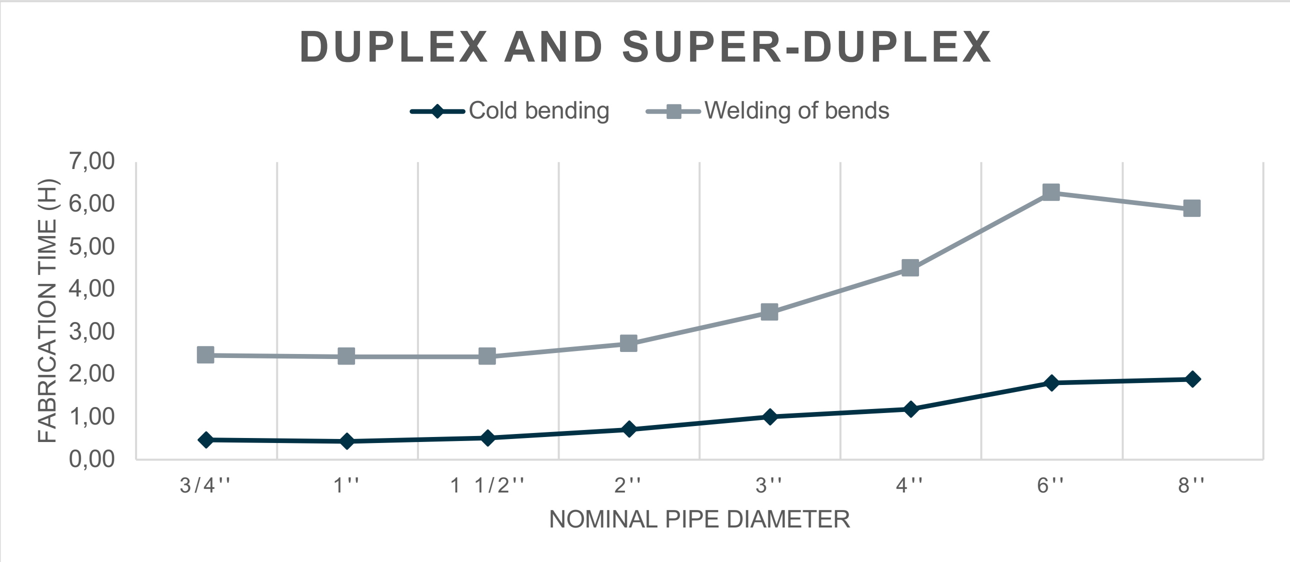

FIGURE 5-2: AVERAGED FABRICATION TIME WITH DUPLEX, SUPER-DUPLEX SS.

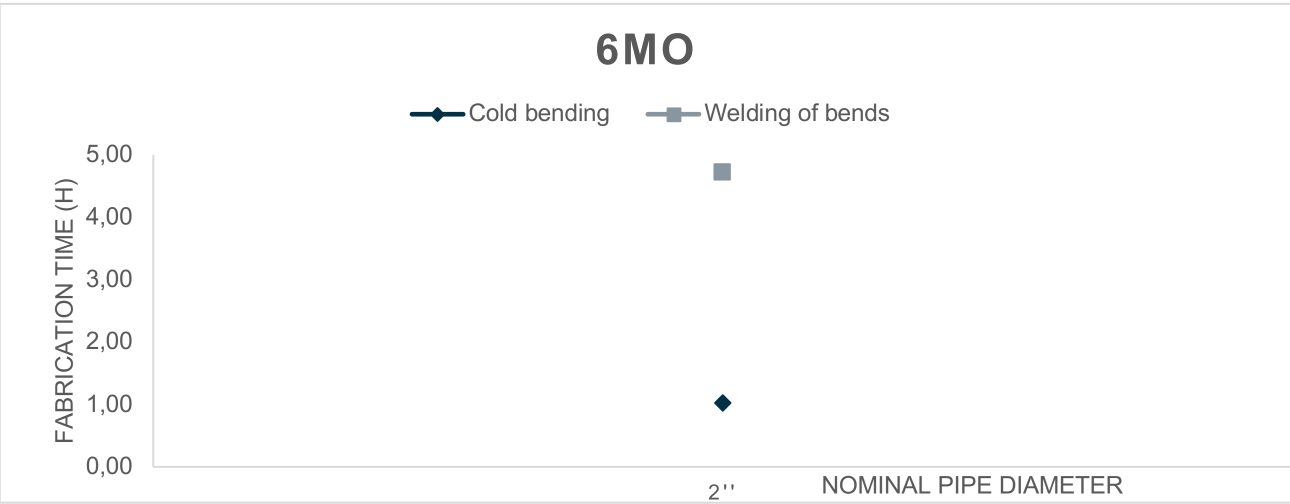

FIGURE 5-3: AVERAGED FABRICATION TIME WITH 6MO SS.

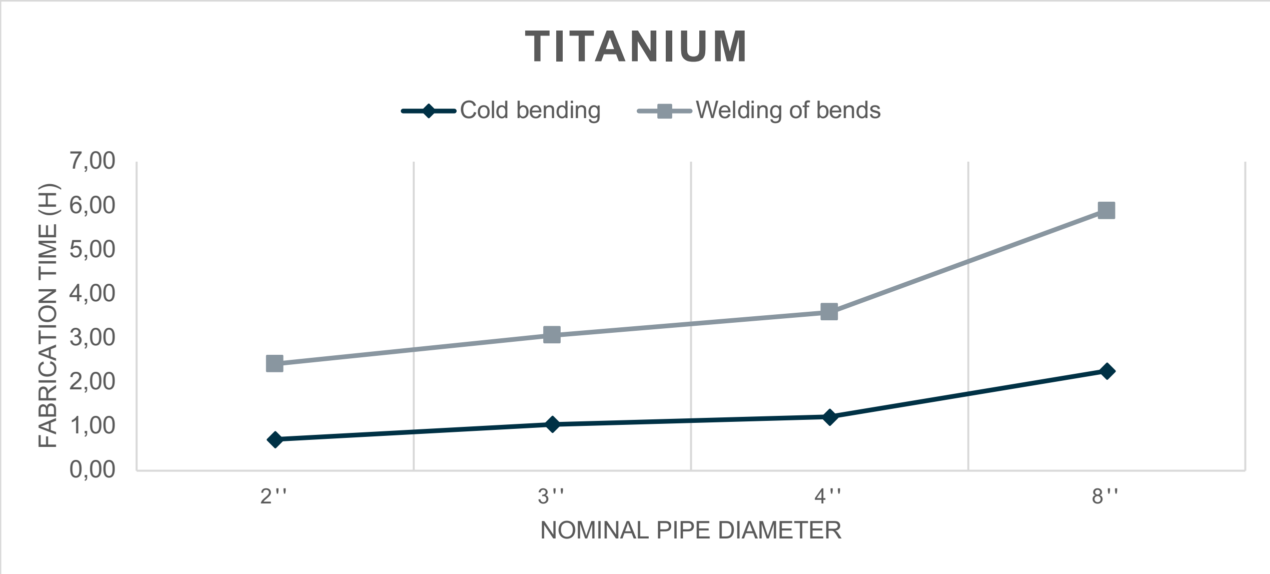

FIGURE 5-4: AVERAGED FABRICATION TIME WITH TITANIUM.

As seen in Figure 5-2, Figure 5-3 and Figure 5-4, cold bending has a lower fabrication time per unit in all the categories. It is also shown in the figures that the fabrication time favours cold bending even more as the nominal pipe diameter increases.

5.2.2 NDT COSTS

There are different requirements regarding NDT for cold bending and welding of bends. The requirements are described in Ch. 2.2.1 for welding of bends and in Ch. 3.2.1 for cold bending. As an example, if the pipe bend is a SS type 316 in NDT group 2 the requirement for NDT are:

For welded connections:

- 10% PMI
- 10% volumetric testing, RT/UT
- 10% surface testing, MT/PT
- 100% visual inspection

For cold bent pipes:

- 10% surface testing, MT/PT
- 100% visual inspection

Overall, welding of bends requires more NDT than cold bending. By summarizing the costs related to additional NDT for cold bent pipes and dividing this on the sum for the NTD costs for the welds we have reduced (due to cold bending instead), the results show that NDT costs were reduced by 11-12% for applicable systems in the reference project.

5.2.3 Material Costs

To visualize the differences in material cost between cold bending and welding of bends, the data were divided into material groups and nominal pipe sizes. Meaning that the groups will contain different pressure ratings (same as in Ch. 5.2.1).

In order to compare the different manufacturing methods against each other, the calculations were performed as follows:

- For cold bending: averaging the price in the different groups for extra pipe material needed to manufacture a cold bent pipe.
- For welding of bends: averaging the cost of elbows in the different groups.

To illustrate the differences between the two methods, the reference line (light grey) at 100% in Figure 5-5, Figure 5-6 and Figure 5-7 represents the average price of elbows for welding of bends. The dark blue line in Figure 5-5, Figure 5-6, and Figure 5-7 represents the price for the additional pipe material needed for cold bending.

Figure 5-5 representing the differences in material cost for Duplex, Super-Duplex bent pipes. The differences in material cost decrease as the nominal pipe diameters increases. The additional material costs for manufacturing a cold bent ¾'' pipe in the reference project costed about 5% in relation to the price of an elbow in the same size.

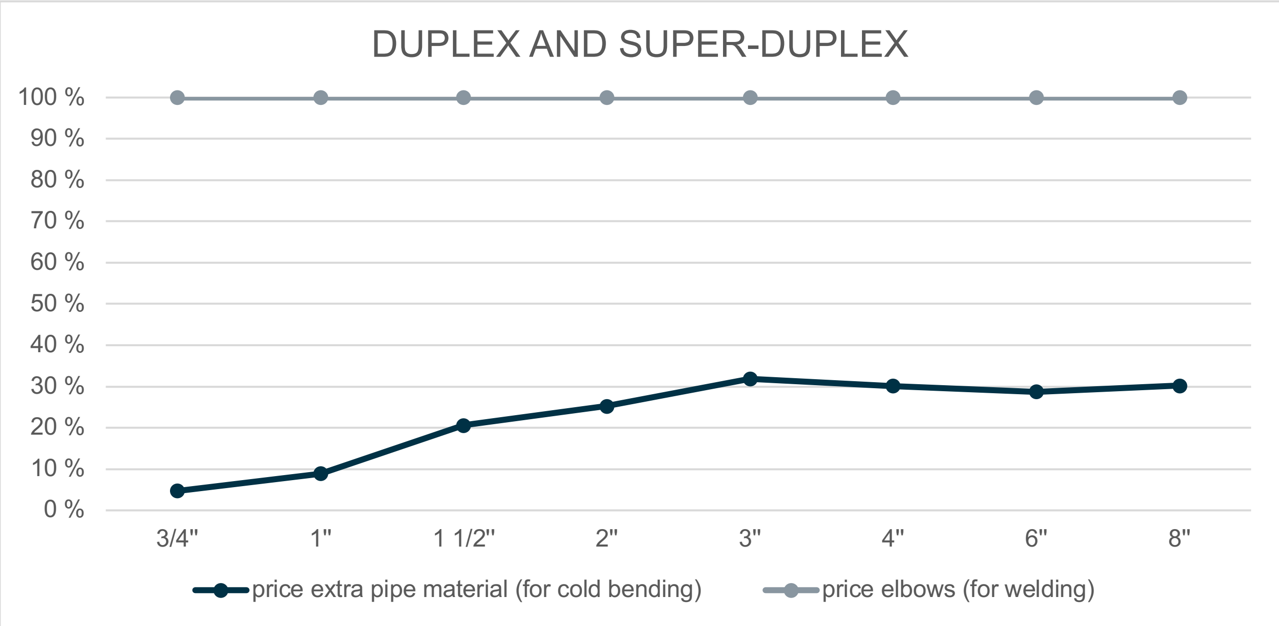

FIGURE 5-5: DUPLEX, SUPER-DUPLEX, DIFFERENCES IN MATERIAL COST FOR BENT PIPES.

There were only data from 2’’ bent 6Mo pipes from the reference project. Results from Figure 5-6 show that additional material cost related to cold bending were about 25% of the additional material costs related to welding of bends in the project.

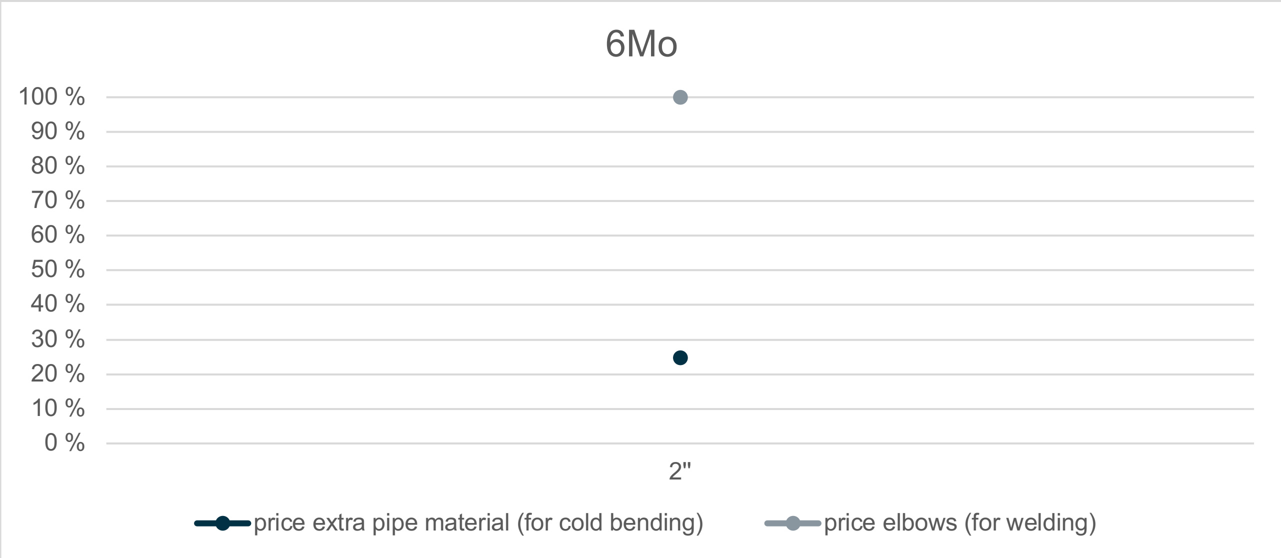

FIGURE 5-6: 6MO, DIFFERENCES IN MATERIAL COST FOR BENT PIPES.

Additional material cost related to cold bent Titanium pipes range from about 22% to 37% of additional costs for welded pipes as seen in Figure 5-7.

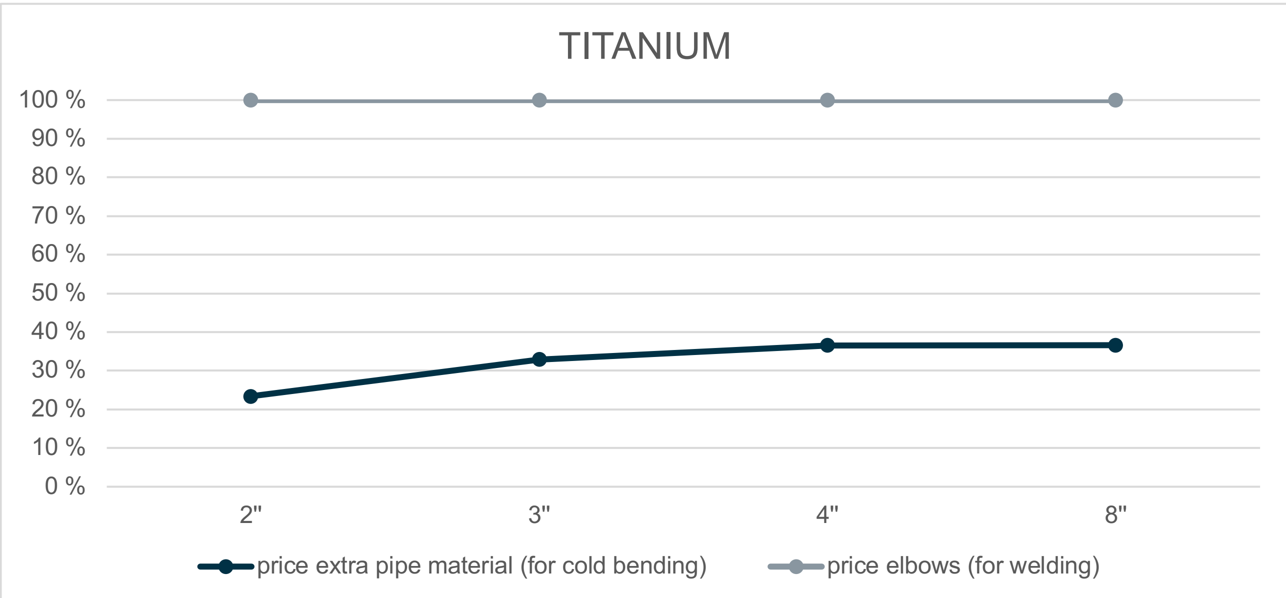

FIGURE 5-7: TITANIUM, DIFFERENCES IN MATERIAL COST FOR BENT PIPES.

6 MULTI-CRITERIA DECISION ANALYSIS

6.1 ANALYTIC HIERARCHY PROCESS (AHP)

In our everyday lives we are faced with multiple choices. What car we should buy, where to live, and so on. Some problems are more complex than others. It may be difficult to decide intuitively, and in other cases nearly impossible.

In cases where we are presented with multiple criteria to consider when choosing a solution, it may be difficult to select a rational and optimal choice. Multi-criteria decision analysis can be used to structure the different criteria and alternatives, and help finding the best solution based on the data available.

For this thesis, analytic hierarchy process (AHP) will be used for its ability to easily structure the different criteria (factors to consider when deciding) and alternatives into a hierarchy, and the possibility to compare both qualitative and quantitative data simultaneously (Samarakoon and Ratnayake, 2015). AHP is a mathematical tool known to be a flexible, robust, and intuitive tool within multi criteria analysis. It uses both math and psychology when analysing. Thomas L. Saaty was a pioneer in AHP and has contributed with several books and studies (Saaty and Vargas, 2001). AHP can be used both professionally and in everyday life making it easier to select an optimal alternative. When using AHP both human judgements, expert opinions and data can be used comparing different alternatives. "In essence, this approach enables the decision maker to develop priorities by converting human judgments (i.e. data, experiences, the intuition and intentions of experts in different disciplines) into numerical values" (Samarakoon and Ratnayake, 2015).

Further explained by Samarakoon and Ratnayake (Samarakoon and Ratnayake, 2015):

"Primarily, AHP is built on the following three underlying concepts:

I. Structuring the decision problem as a hierarchy of goals, criteria, and alternatives;
II. Pairwise comparison of elements at each level of the hierarchy with respect to each criterion on the preceding level; and
III. Vertically synthesizing the judgements over the different levels of the hierarchy"

To conduct the AHP analysis several stages need to be performed (Antosz and Ratnayake, 2019). Figure 6-1 shows a visualization of the process followed in this thesis:

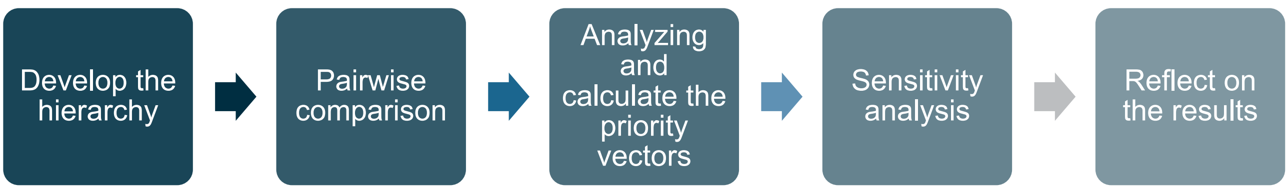

FIGURE 6-1: FLOW OF THE AHP PROCESS.

6.1.1 HIERARCHY

First step in the AHP analysis is to create the hierarchy. The hierarchy is an important task in the analysis. In this step we decide which factors we want to include in the analysis, tangible and intangible. It is necessary to include enough relevant information to represent the problem as thoroughly as possible, but still being able to catch small changes in the elements (Saaty and Vargas, 2001). An example on how to structure a hierarchy is shown in Figure 6-2 (Samarakoon and Ratnayake, 2015), where each box is representing a node. The hierarchy consist of multiple levels, but in general it consists of:

- G, a goal, here one need to establish the goal of the analysis, what are we trying to find out?
- C, criteria, define which criteria (factors) we want to evaluate
    - SB, it is also possible to have sub- and sub-sub-criteria connected to the criteria
- A, the different alternatives

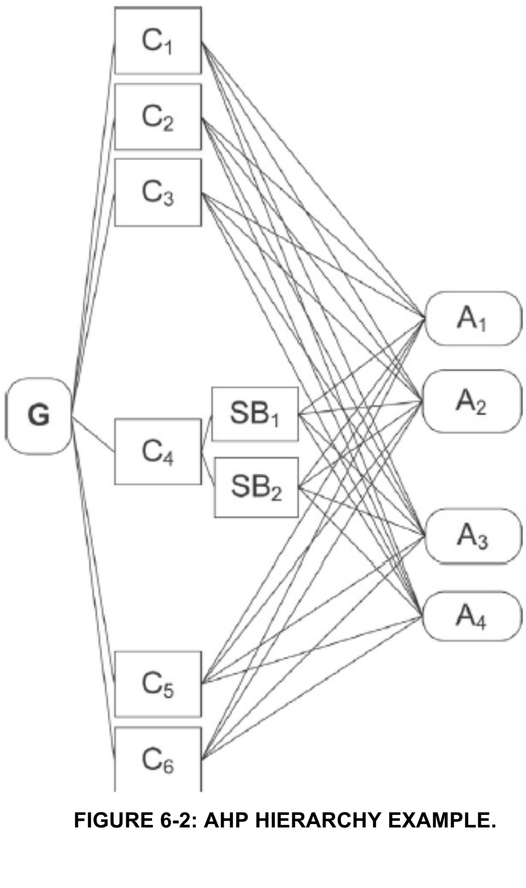

FIGURE 6-2: AHP HIERARCHY EXAMPLE.

Hierarchy structure

For this thesis it was decided to develop 5 hierarchies. One for each of the materials selected:

- Duplex, Super-Duplex stainless steel
- TP316
- 6Mo
- Titanium gr. 2
- CMn steel: A106 gr. B and API 5L gr. B

The hierarchies were developed in collaboration with experts from relevant fields. It was decided to compare cold bending and welding of bends in situations where it is possible use both, therefore the criteria and sub-criteria were selected based on this.

The elements:

The elements selected for this AHP analysis are listed below with a brief explanation.

Goal:

"Select the best technique to manufacture a bend", the purpose of this thesis is to compare the two different manufacturing methods, therefore the goal of this analysis is to be able to select between cold bending and welding of bends.

Criteria:

- Material quality in relation to fabrication
- Cost, related to manufacturing
- Fabrication time, approximate time to manufacture

Sub-criteria:

- ½''-1 ½'', grouping of dimensions (nominal pipe size) applicable for both alternatives
- 2"-4", grouping of dimensions (nominal pipe size) applicable for both alternatives
- 6"-8", grouping of dimensions (nominal pipe size) applicable for both alternatives
- SCH 10-40, grouping in different wall thicknesses, called pipe Schedule
- SCH 60-80, grouping in different wall thicknesses, called pipe Schedule
- SCH 100- XXS, grouping in different wall thicknesses, called pipe Schedule

Hierarchy 1, Duplex, Super-Duplex

Figure 6-3 illustrates the AHP hierarchy structure for comparison of the cold bending and welding of bends with respect to manufacture a Duplex, Super-Duplex SS bend. The alternatives will be prioritized in relation to the criteria (level 1) and six sub-criteria (level 2).

Duplex and Super-Duplex are ferritic/austenitic stainless steels. Duplex consist of 22% Cr and Super-Duplex consists of 25% Cr (NORSOK, 2016, p. 7). This type of materials are widely used in the oil and gas industry, and often referred to as the “workhorse” within materials selection.

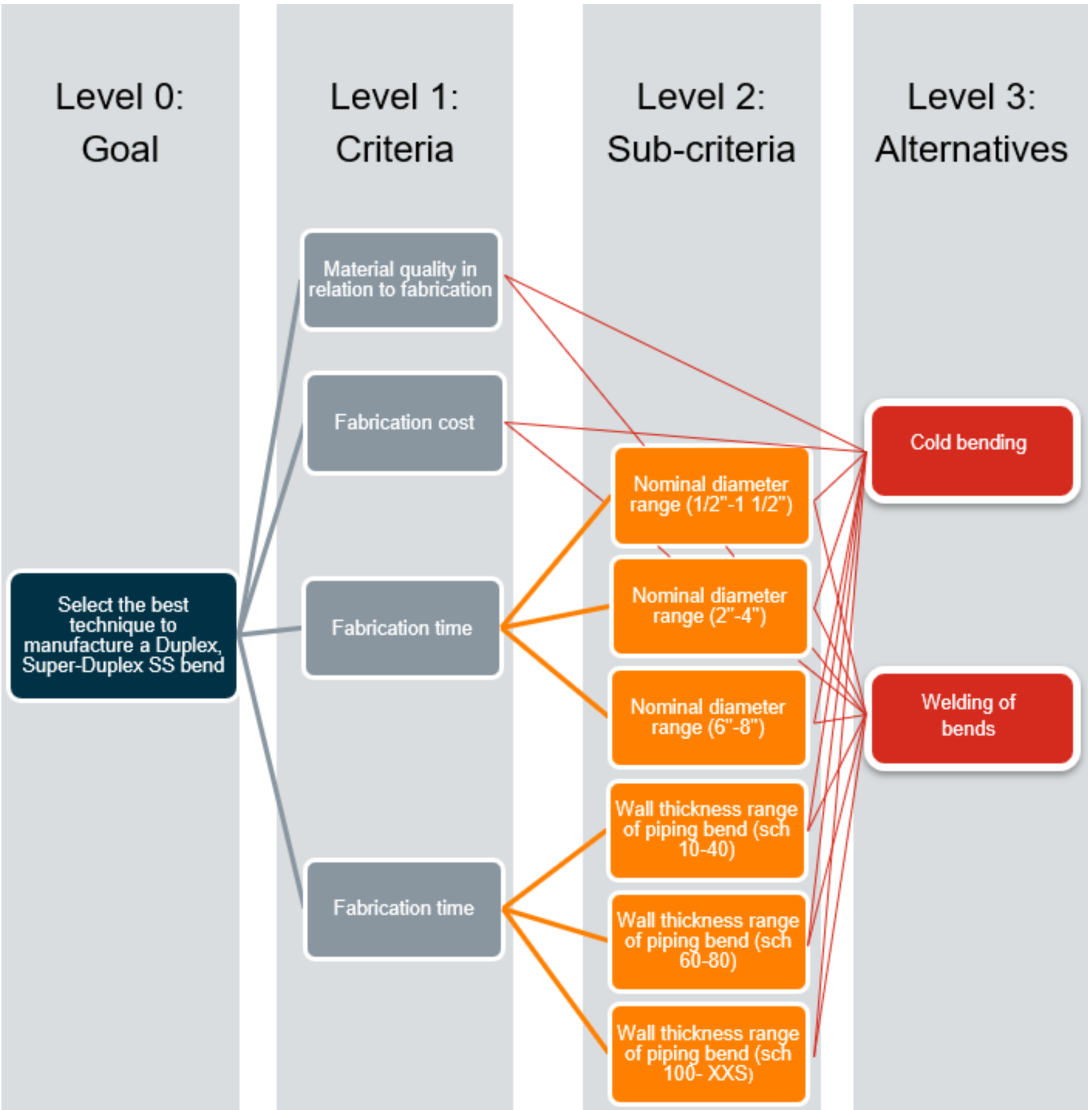

FIGURE 6-3: AHP HIERARCHY FOR COMPARISON OF COLD BENDING AND WELDING OF BENDS, WITH DUPLEX AND SUPER-DUPLEX SS MATERIAL.

Hierarchy 2, 6Mo

Figure 6-4 illustrates the AHP hierarchy structure for comparison of cold bending and welding of bends with respect to manufacture a 6Mo bend. The alternatives will be prioritized in relation to the criteria (level 1) and six sub-criteria (level 2).

6Mo is an austenitic stainless steel, consisting of alloys with 6 % Mo (NORSOK, 2020, p. 4). The material is known for its high resistant against corrosion.

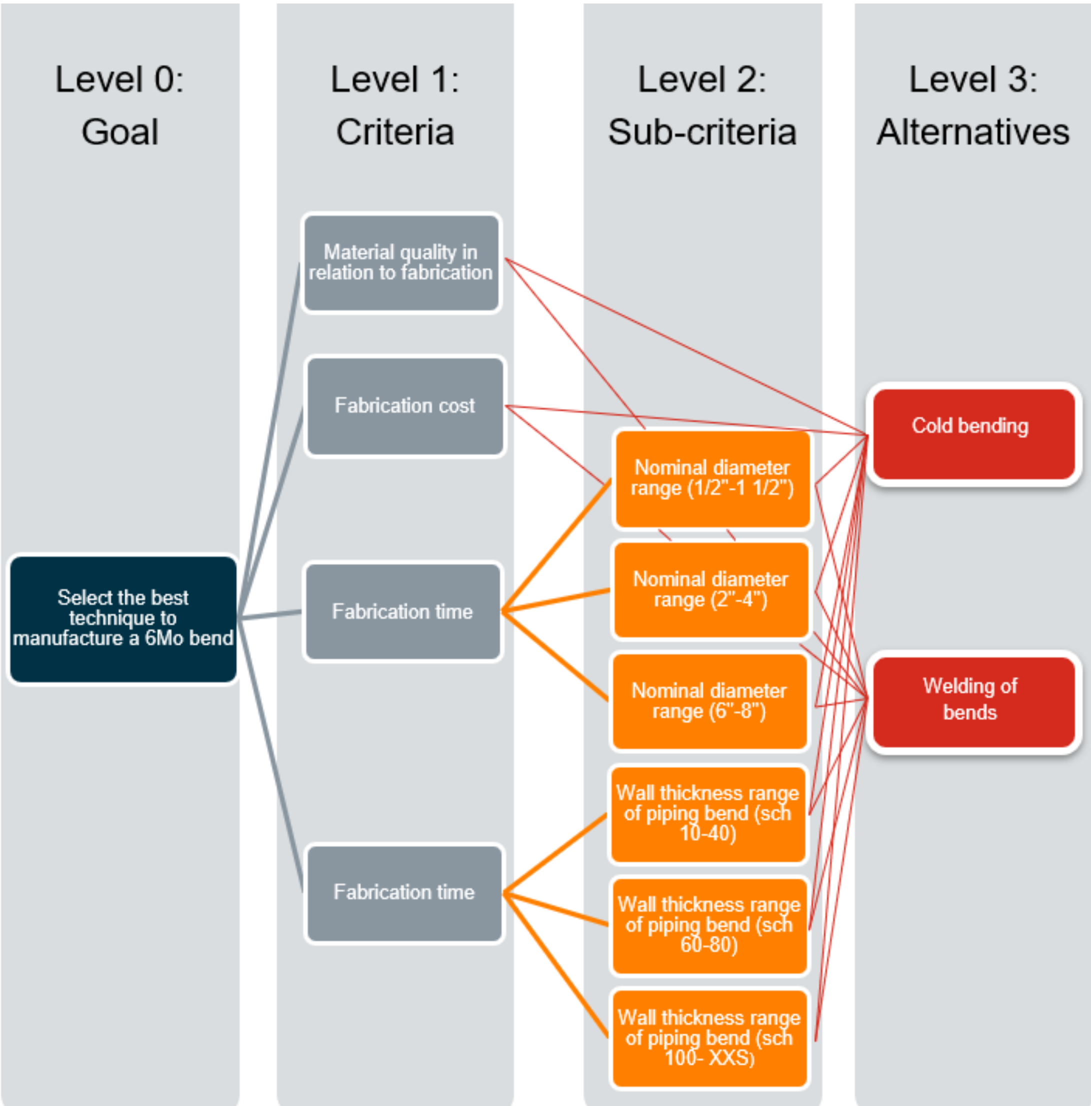

FIGURE 6-4: AHP HIERARCHY FOR COMPARISON OF COLS BENDING AND WELDING OF BENDS, WITH 6MO MATERIAL.

Hierarchy 3, TP316

Figure 6-5 illustrates the AHP hierarchy structure for comparison of cold bending and welding of bends with respect to manufacture a TP316 bend. The alternatives will be prioritized in relation to the criteria (level 1) and six sub-criteria (level 2).

TP316 is an austenitic stainless steel containing alloys "with approximately 2,5 % Mo of type AISI 316" (NORSOK, 2020, p. 4).

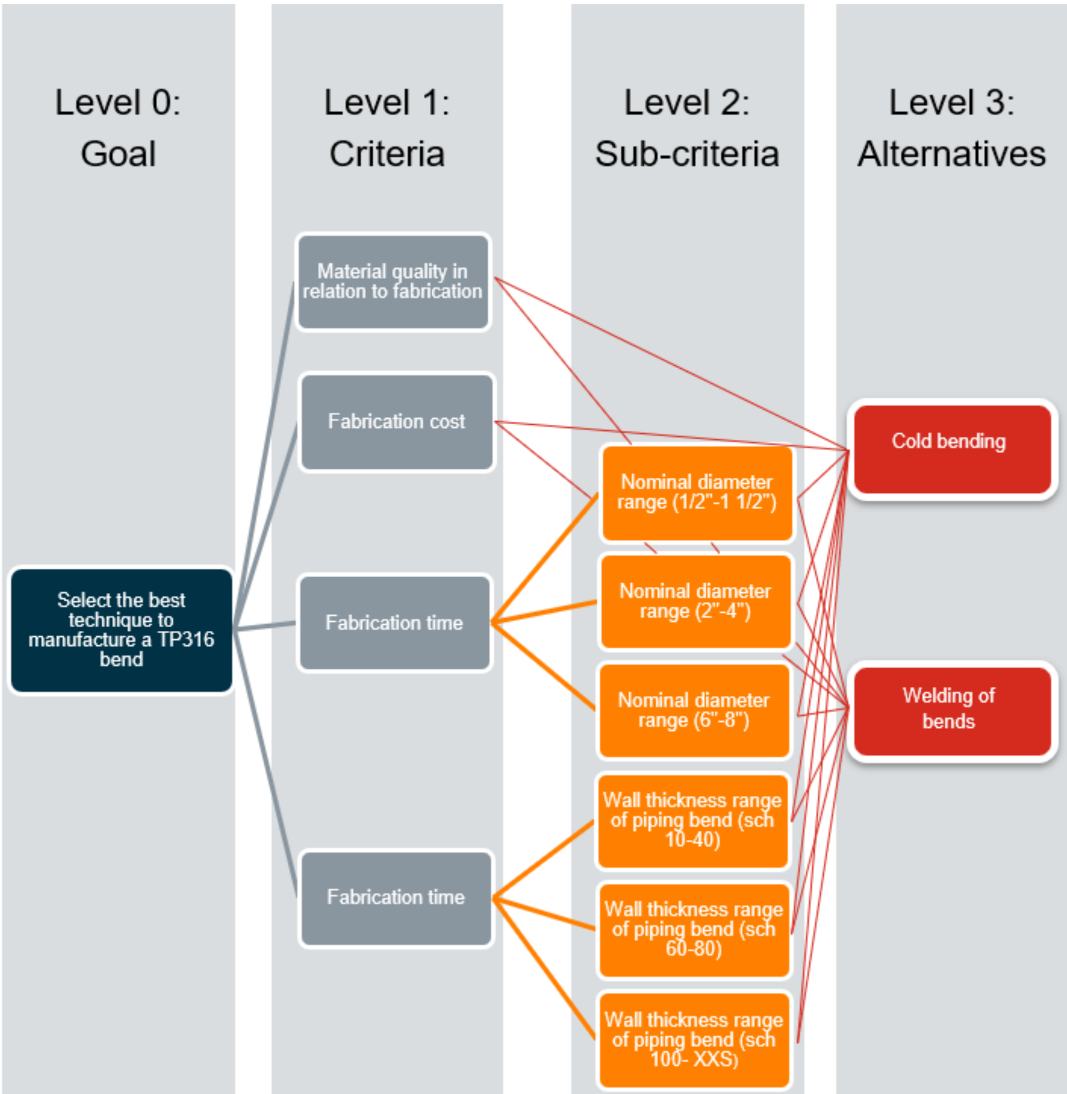

FIGURE 6-5: AHP HIERARCHY FOR COMPARISON OF COLD BENDING AND WELDING OF BENDS, WITH TP316 MATERIAL.

Hierarchy 4, Titanium gr. 2

Figure 6-6 illustrates the AHP hierarchy structure for comparison of cold bending and welding of bends with respect to manufacture a Titanium gr. 2 bend. The alternatives will be prioritized in relation to the criteria (level 1) and six sub-criteria (level 2).

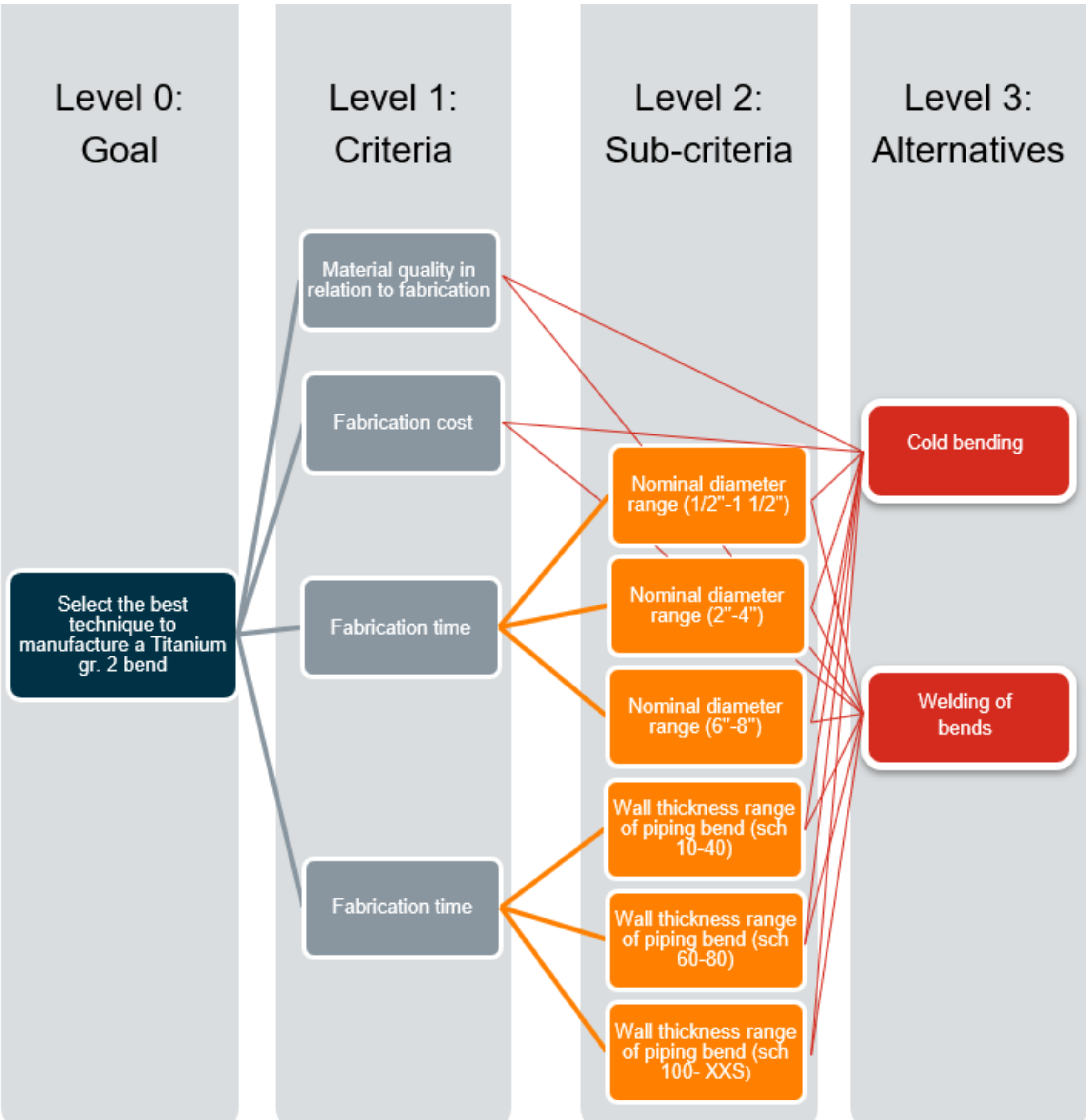

FIGURE 6-6: AHP HIERARCHY FOR COMPARISON OF COLD BENDING AND WELDING OF BENDS, WITH TITANIUM GR. 2.

Hierarchy 5, CMn steels: A106 gr. B and API gr. B

Figure 6-7 illustrates the AHP hierarchy structure for comparison of cold bending and welding of bends with respect to manufacture a bend of CMn steels type A106 gr. B and API gr. B. The alternatives will be prioritized in relation to the criteria (level 1) and six sub-criteria (level 2).

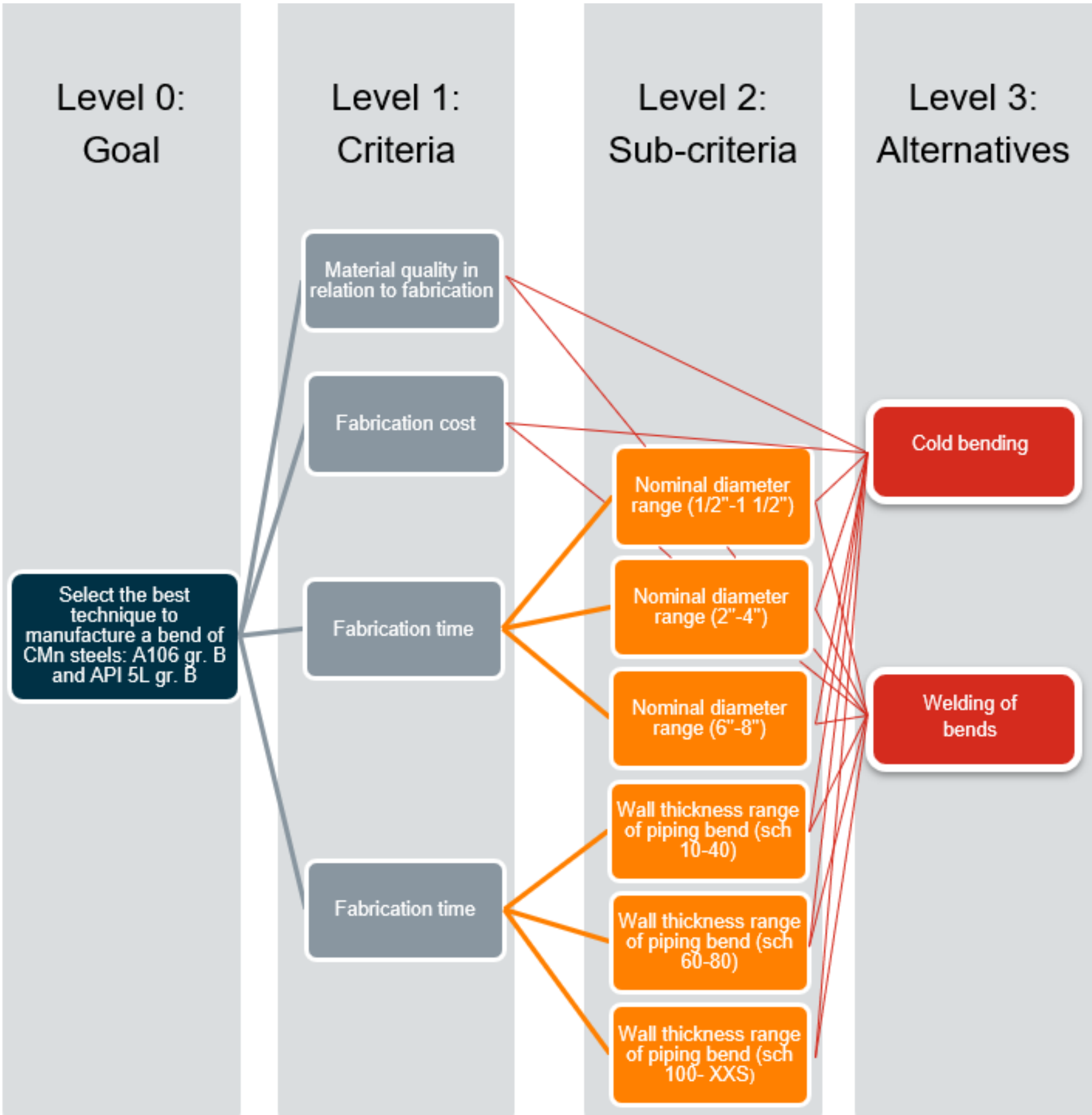

FIGURE 6-7: AHP HIERARCHY FOR COMPARISON OF COLD BENDING AND WELDING OF BENDS, WITH CMN STEELS: A106 GR. B AND API 5L GR. B.

6.1.2 Pairwise comparisons

Next step in the process is to establish priorities and evaluate each node against each of its peers in relation to its parent node, called pairwise comparisons (Samarakoon and Ratnayake, 2015). This is conducted with help from experts from relevant fields and data collected from the reference project (Ch. 5.1). In order to gather expert assessments and convert them into numerical values, a questionnaire was developed. Saaty's fundamental scale for assessing the importance of elements, Table 6-1 (Saaty and Vargas, 2001, p. 6), were used as a reference in the questionnaire for ranking of the elements.

TABLE 6-1: SAATY'S FUNDAMENTAL SCALE FOR ASSESSING THE IMPORTANCE OF ELEMENTS.

Intensity of importance	*Definition*	*Explanation*
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance one over another	Experience and judgement favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, and 8	Intermediate values between the two adjacent judgments	When compromise is needed

Figure 6-8 shows a sample of questions from the questionnaire, where cold bending and welding of bends are compared in relation to the different grouping of wall thicknesses from the hierarchy. These questions are conducted systematically for all the different elements (i.e., criteria, sub-criteria, and alternatives), until all elements have been assigned a weight.

A node is prioritized over another if it contributes, influence or benefit greater relative to the parent node. For instance, if Schedule 60-80 has moderate importance (Table 6-1) over Schedule 10-40 in relation to wall thickness a mark will be put at "3" on the right side in the questionnaire (as shown in Figure 6-4). Elements (nodes) given a full number is regarded as favourably, and elements (nodes) regarded less favourable is given a fraction (Samarakoon and Ratnayake, 2015).

Level 2. Fabrication time:

How much more strongly does "option A" contribute to, dominate, influence, satisfy or benefit, than does "option B" in relation to ***Fabrication time*** for a bend?

Option A	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Option B
Sch. 10-40											X							Sch. 60-80
Sch. 10-40												X						Sch. 100-XXS
Sch. 60-80											X							Sch. 100-XXS

FIGURE 6-8: SAMPLE QUESTION FROM THE AHP QUESTIONNAIRE.

During the evaluation several judgements are collected from experts. If the answers differ, then geometric mean ($\overline{w}$) will be used to find the average judgement value. Geometric mean is given by Eq. (10):

$$\overline{w} = \left(\prod_{i=1}^{n} w_i\right)^{1/n} = \sqrt[n]{w_1 w_2 \ldots . w_n} \qquad (10)$$

After gathering all the judgements and data the values (weights) will be put into a pairwise comparison matrix (PCM). The PCM, $\mathbf{A}$, for comparing n elements (nodes) is given by:

$$\boldsymbol{A} = [\boldsymbol{a_{ij}}] \text{ , where } \quad a_{ji} = \left[\frac{\mathbf{1}}{\boldsymbol{a_{ij}}}\right], \quad \boldsymbol{a_{ii}} = \mathbf{1}, (\mathbf{1} \le \boldsymbol{i} \le \boldsymbol{n}) \text{ and } (\mathbf{1} \le \boldsymbol{j} \le \boldsymbol{n}) \qquad (11)$$

The PCM ($\mathbf{A}$) has a form as follows:

$$\boldsymbol{A} = \begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 & & w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \cdots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & & w_3/w_n \\ & \vdots & & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \cdots & w_n/w_n \end{bmatrix} \qquad (12)$$

And $w = [w_1 \quad w_2 \quad w_3 \quad \cdots \quad w_n]$

As an example, Table 6-2 shows a PCM from the sample question from the questionnaire (Figure 6-8).

Steps to evolve the PCM:

I. The diagonal elements are always one
II. Start filling up the upper triangular matrix
   - If the mark is on the left side of 1 (or 1) write the actual value
   - If the mark is on the right side of 1 write the reciprocal value
III. The lower triangular matrix is filled up using the reciprocal values from the upper triangular matrix (i.e., a_{ji} in Eq. (11))

TABLE 6-2: PCM (A) EXAMPLE FROM THE QUESTIONNAIRE.

	Sch. 10-40	Sch. 60-80	Sch. 100-XXS
Sch. 10-40	1	1/3	1/4
Sch. 60-80	3	1	1/3
Sch. 100-XXS	4	3	1

Upper triangular matrix

Lower triangular matrix

6.1.3 PRIORITY VECTORS AND CONSISTENCY

There are several ways to derive the vector of priorities from the matrix A (Eq. (12)) due to emphasis on consistency the eigenvector formulation is recommended (Saaty and Vargas, 2001):

$$Aw = nw$$

$$Aw = \begin{bmatrix} w_1/w_1 & w_1/w_2 & w_1/w_3 & & w_1/w_n \\ w_2/w_1 & w_2/w_2 & w_2/w_3 & \dots & w_2/w_n \\ w_3/w_1 & w_3/w_2 & w_3/w_3 & & w_3/w_n \\ & \vdots & & \ddots & \vdots \\ w_n/w_1 & w_n/w_2 & w_n/w_3 & \dots & w_n/w_n \end{bmatrix} * \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} nw_1 \\ nw_2 \\ nw_3 \\ \vdots \\ nw_n \end{bmatrix} = nw$$

(13)

Consistency analysis

To check if the expert's judgements is consistent, a consistency analysis is performed:

"As the matrix A has a special form (i.e., each row is a constant multiple of the first row), the rank of the matrix is one, and except for one eigenvalue, all the other eigenvalues of the matrix A are zero. However, as the sum of the eigenvalues of a positive matrix is equal to the trace of the matrix, the nonzero eigenvalue has a value of n (i.e., the size of matrix). This is referred to as λ_{max} and used for consistency analysis" (Samarakoon and Ratnayake, 2015). If there are small errors and inconsistencies in the judgements and, matrix w is not known and the values for the PCM have been estimated, then the eigenvalue problem for the inconsistent case is:

$$Aw = \lambda_{max} w \qquad (14)$$

where $\lambda_{max} \geq n$ and other λ are approximately zero ($\lambda \sim 0$)

"The estimates of weights for the activities are calculated by normalizing the eigenvector corresponding to the largest eigenvalue in Eq. (15). The normalization is performed by summing each column and then dividing each column entry by its respective column sum" (Samarakoon and Ratnayake, 2015). The normalization process is given by:

$$a' = [a_{ij}'] \text{ where } a'_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{ik}} \text{ for } (1 \leq i \leq n), (1 \leq j \leq n) \text{ and } (1 \leq k \leq n) \qquad (15)$$

"The average value in each row of the normalized matrix is calculated to obtain the relative weights or eigenvector, which is determined by" (Samarakoon and Ratnayake, 2015):

$$W = [w_k] \text{ where } w_k = \sum_{i=1}^{n} \frac{a_{ij}'}{n} \text{ for } (1 \leq i \leq n) \qquad (16)$$

The more consistent the judgements are, the closer λ_{max} is to n. Meaning that if there is perfect consistency then $\lambda_{max} = n$. Therefore, it is possible to use the difference $(\lambda_{max} - n)$ as a measure of inconsistency. Consistency index (CI) (with the previous statement as background) is defined in Eq. (17) and representing the average of the remaining eigenvalues (Samarakoon and Ratnayake, 2015):

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \qquad (17)$$

“To derive a meaningful interpretation of the CI, random pairwise comparisons have been simulated at the inception of the AHP for different sizes of matrices. The calculations have been performed for calculating CIs and arriving at an average CI for random judgements for each size of matrix (i.e. referred to as random consistency index (RCI).” (Samarakoon and Ratnayake, 2015) The size of the matrix vs. RCI is illustrated in Table 6-3.

TABLE 6-3: SIZE OF MATRIX VS. RANDOM CONSISTENCY INDEX.

n	1	2	3	4	5	6	7	8	9	10
RCI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The consistency ratio (CR) is found by a comparison between CI and RCI (average CI) for a set of judgements, shown in Eq. (18) (Samarakoon and Ratnayake, 2015):

$$CR = \frac{CI}{RCI} \qquad (18)$$

The judgements are consistent if CR < 0.1 (10%) (Samarakoon and Ratnayake, 2015). Meaning that if CR is bigger than 10% the subjective judgements should be re-checked, and the problem may need more studying.

Consistency analysis example

Sometimes it is easier to understand something by seeing an example, therefore I will show how the consistency analysis can be conducted for the sample question from the AHP analysis (Figure 6-8). It is noted that following example is an approximation, the eigenvector derivation process should be used for more accuracy.

Since the PCM (Table 6-2) already have been made, the normalization process can begin. As explained in Eq. (15) and above about normalization: "summing each row and then dividing each column entry by its respective sum", provides the result shown in Table 6-4:

TABLE 6-4: NORMALIZED PCM FROM SAMPLE QUESTION IN AHP.

	Sch. 10-40	Sch. 60-80	Sch. 100-XXS
Sch. 10-40	1/8	1/13	3/19
Sch. 60-80	3/8	3/13	4/19
Sch. 100-XXS	1/2	9/13	12/19

Then, the normalized principal eigenvector or weight can be obtained by following Eq. (16) (averaging across the rows):

$$w = \frac{1}{3}\begin{bmatrix} \frac{1}{8} + \frac{1}{13} + \frac{3}{19} \\ \frac{3}{8} + \frac{3}{13} + \frac{4}{19} \\ \frac{1}{2} + \frac{9}{13} + \frac{12}{19} \end{bmatrix} = \begin{bmatrix} 0.120 \\ 0.272 \\ 0.608 \end{bmatrix}$$

Since we have w available in a normalized form, an "easy" way to calculate (or estimate) λ_{max} is to add the columns of A (Table 6-2) and multiply the resulting vector by the priority vector w (i.e. $\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij}w_j$) (Saaty and Vargas, 2001):

$$\lambda_{max} = (1 + 3 + 4) * 0{,}120 + \left(\frac{1}{3} + 1 + 3\right) * 0{,}272 + \left(\frac{1}{4} + \frac{1}{3} + 1\right) * 0{,}608 = 3.101$$

CI is calculated according to Eq. (17), with n=3 (3 comparisons in this case):

$$CI = \frac{(3.01 - 3)}{(3 - 1)} = 0.05$$

Since n=3 leads to RCI=0.58 (from Table 6-3), and CR can be calculated (Eq. (18)):

$$CR = \frac{0.05}{0.58} = 0.087$$

CR < 0.1 ($0.087 < 0.1$), thus the judgement in the sample question (Figure 6-8) is consistent based on this approximation.

6.2 Analysis in AHP

6.2.1 Expert Choice Software

Analysing in AHP manually takes time (illustrated in an example in Ch. 6.1.3) and the probability of incorrect calculation increases. After recommendation from Prof. Ratnayake the software program Expert Choice was selected to perform the AHP analysis for this thesis. In Expert Choice software there are five types of sensitivity analysis (Expert Choice):

I. **Performance sensitivity**
   - Graphs that will display how the alternatives perform with respect to all objectives and overall.

II. **Dynamic sensitivity**
   - Here it's possible to dynamically change the priorities of the objectives to determine how these changes affect the priorities of the alternative choices.

III. **Gradient sensitivity**
   - Consists of graphs that illustrates the alternatives priorities with respect to a single object at a time.

IV. **Head-to-Head sensitivity**
   - Show how two different alternatives compared to one another against the criteria/sub-criteria in a decision.

V. **Two-dimensional sensitivity**
   - Illustrates how two different alternatives perform with respect to any criteria/sub-criteria. This type of sensitivity analysis has not been included in this thesis.

6.2.2 Synthesize

Synthesis is the process of weighting and prioritizing the model after evaluations are made to yield the result (Expert Choice). Each node is applied a local priority and its parent node a global priority to obtain the global priorities for nodes thru the model. The global priorities are then summed to yield overall. The results are represented as bar graphs in Figure 6-9, Figure 6-10, Figure 6-11, Figure 6-12, and Figure 6-13. The best choice based on the data taken into consideration is the alternative with the longest bar, that is the highest priority. Screenshots for the figures are taken from Expert Choice software.

Figure 6-9 shows that cold bending is the preferred alternative to manufacture a 6Mo bend with criteria given in the analysis. Cold bending was preferred with 87,6%, and welding of bends with 12,4%.

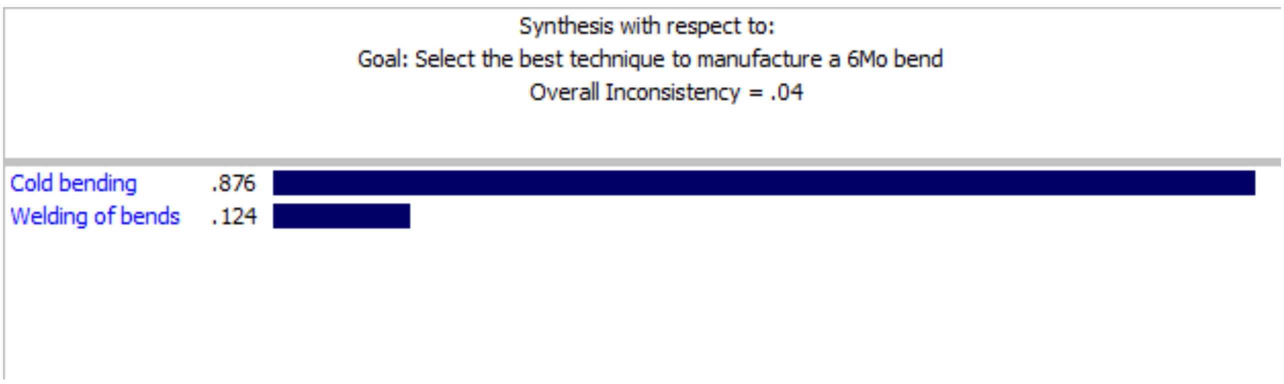

FIGURE 6-9: SYNTHESIS WITH RESPECT TO THE GOAL "SELECT THE BEST TECHNIQUE TO MANUFACTURE A 6MO BEND".

Figure 6-10 shows that cold bending is the preferred alternative to manufacture a bend of CMn steels: A106 gr. B and API 5L gr. B with criteria given in the analysis. Cold bending was preferred with 78,0%, and welding of bends with 22,0%.

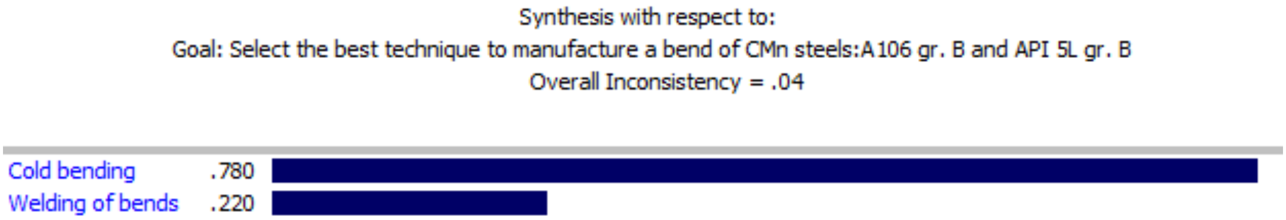

FIGURE 6-10: SYNTHESIS WITH RESPECT TO THE GOAL "SELECT THE BEST TECHNIQUE TO MANUFACTURE A BEND OF CMN STEELS: A106 GR. B AND API 5L GR. B BEND".

Figure 6-11 shows that cold bending is the preferred alternative to manufacture a Duplex, Super-Duplex bend with criteria given in the analysis. Cold bending was preferred with 86,1%, and welding of bends with 13,9%.

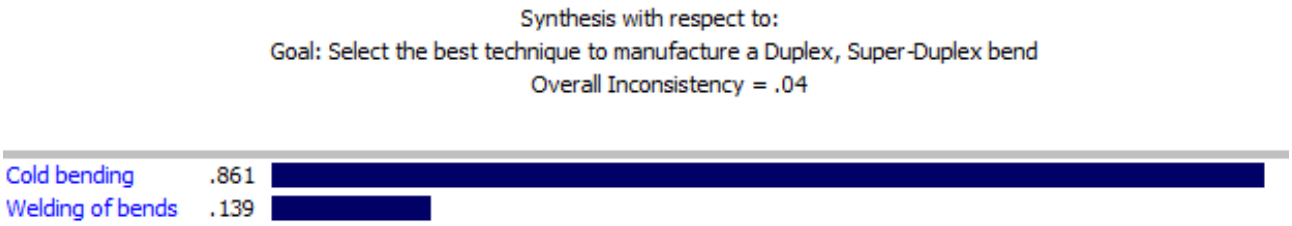

FIGURE 6-11: SYNTHESIS WITH RESPECT TO THE GOAL "SELECT THE BEST TECHNIQUE TO MANUFACTURE A DUPLEX, SUPER-DUPLEX BEND".

Figure 6-12 shows that cold bending is the preferred alternative to manufacture a Titanium gr. 2 bend with criteria given in the analysis. Cold bending was preferred with 86,3%, and welding of bends with 13,7%.

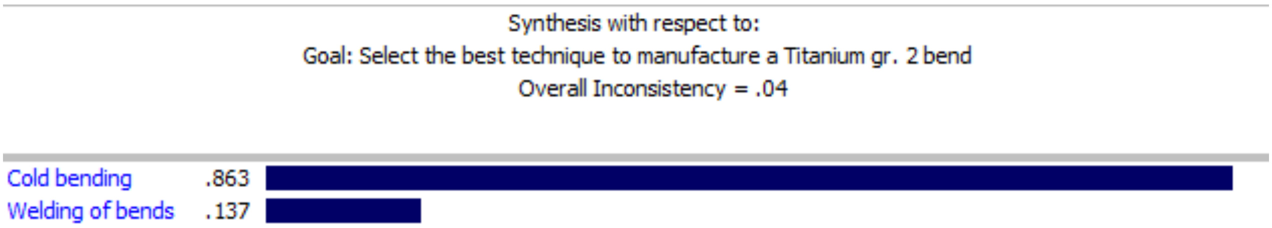

FIGURE 6-12: SYNTHESIS WITH RESPECT TO THE GOAL "SELECT THE BEST TECHNIQUE TO MANUFACTURE A TITANIUM GR. 2 BEND".

Figure 6-13 shows that cold bending is the preferred alternative to manufacture a TP316 bend with criteria given in the analysis. Cold bending was preferred with 82,1%, and welding of bends with 17,9%.

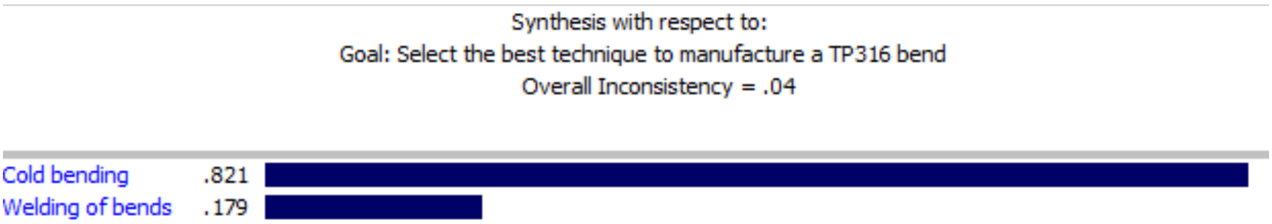

FIGURE 6-13: SYNTHESIS WITH RESPECT TO THE GOAL "SELECT THE BEST TECHNIQUE TO MANUFACTURE A TP316 BEND".

Consistency

In all the five analysis the overall consistency was 0,04, which is within good margin of the limit 0,1. Thus the judgements from the questionnaires are consistent.

Overall synthesis

Figure 6-14 (created in Excel) illustrates overall synthesis for all the five analyses. As illustrated, bends manufactured with 6Mo material have the highest preference for cold bending, favoured with 87,6%, followed by Titanium gr. 2 with 86,3% preference for cold bending.

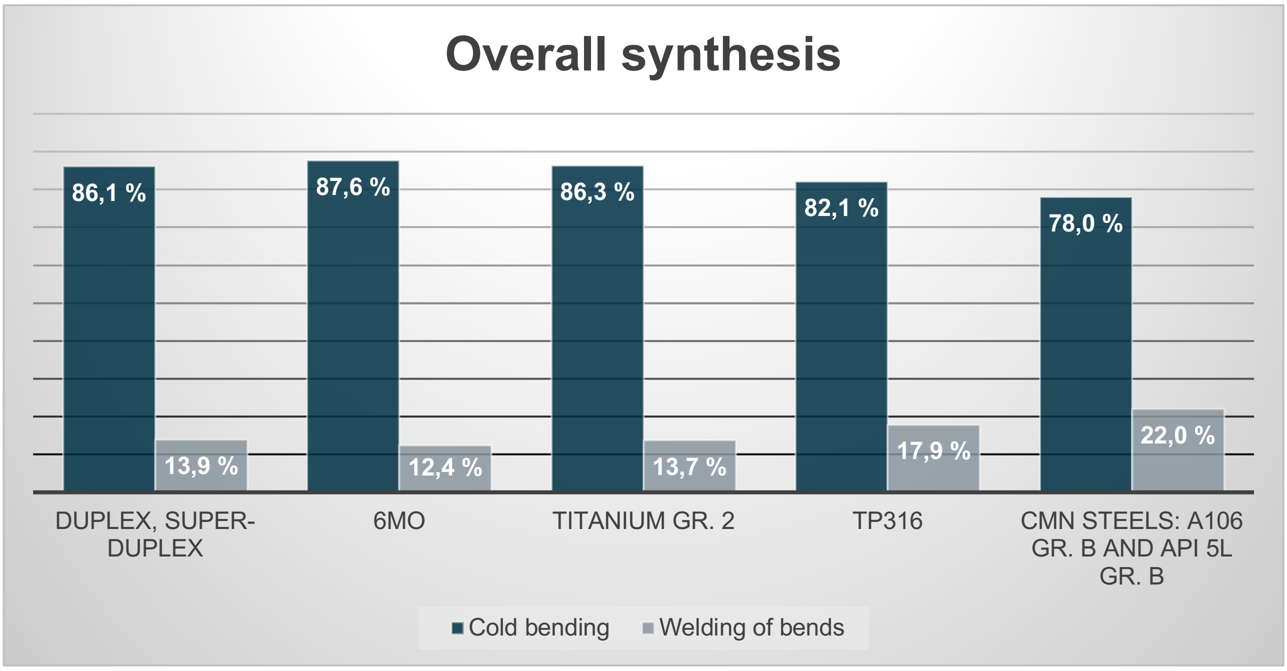

FIGURE 6-14: OVERALL SYNTHESIS FOR ALL THE FIVE ANALYSIS.

6.2.3 DUPLEX AND SUPER-DUPLEX

In Figure 6-15 the criteria priorities derived from pairwise comparisons with respect to the goal are visualised. The relationship between the criteria with respect to the goal node is the same for all five hierarchies in the analysis. Out of the three criteria, fabrication cost has the highest priority with 41,5%, followed by fabrication time with 24,4% and material quality with 9,8% priority.

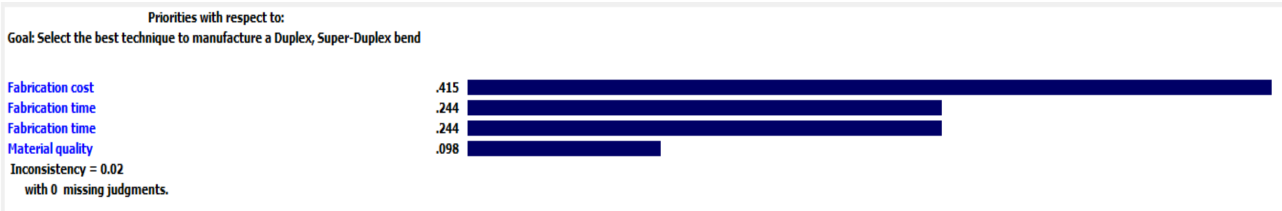

FIGURE 6-15: PRIORITIES WITH RESPECT TO THE GOAL "SELECT THE BEST TECHNIQUE TO MANUFACTURE A DUPLEX, SUPER-DUPLEX BEND".

Performance sensitivity

In Figure 6-16 and Figure 6-17 the performance graphs display how cold bending and welding of bends perform with respect to nominal pipe diameters (Figure 6-16) and wall thicknesses (Figure 6-17) as well as overall. On the left side y-axis, the sub-criteria priorities (Obj%) can be read, and on the right side of the y-axis the alternative priorities (Alt%) with respect to each sub-criterion can be read.

As illustrated in Figure 6-16, nominal pipe diameter 6''-8'' has the highest priority in relation to its parent node (fabrication time), meaning it takes the longest time to fabricate. Cold bending is prioritized highest in comparison with welding of bends when manufacturing 6''-8'' nominal pipe diameter bends with duplex, super-duplex material.

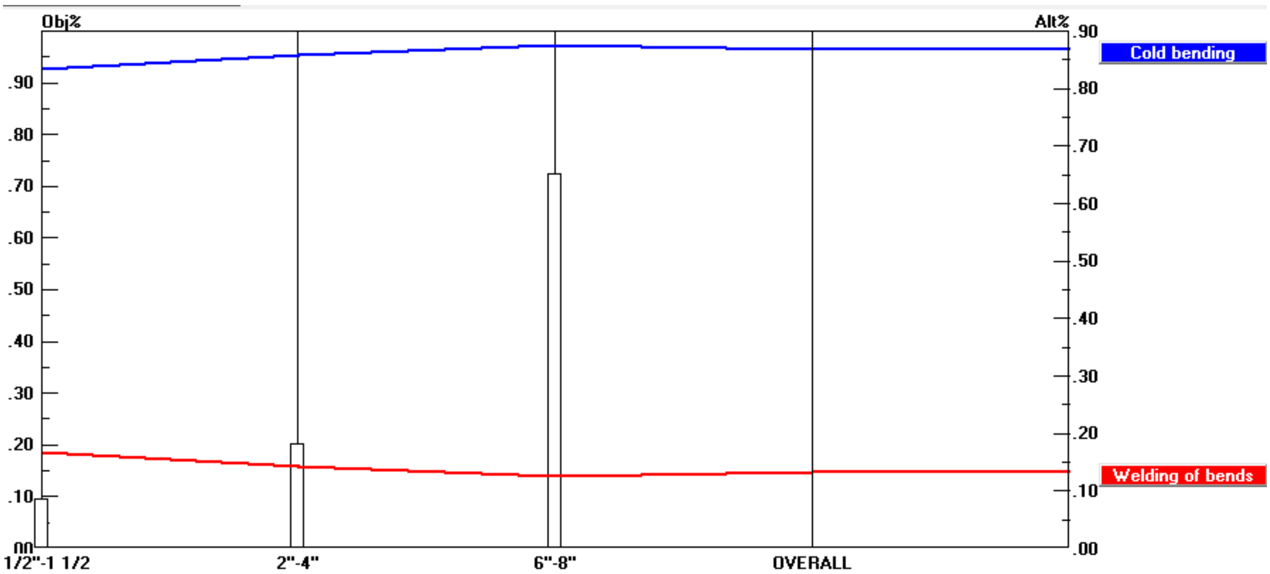

FIGURE 6-16: PERFORMANCE SENSITIVITY RESULTS OF DUPLEX, SUPER-DUPLEX BENDS NOMINAL PIPE DIAMETERS WITH RESPECT TO FABRICATION TIME CRITERIA.

As seen in Figure 6-17 the performance sensitivity results of duplex, super-duplex bends wall thicknesses with respect to fabrication time shows that fabrication time increases as the wall thicknesses increases. Meaning that pipe wall thickness SCH 100-XXS has the highest priority in relation to fabrication time (takes the longest time to fabricate) of the different wall thicknesses, and welding of bends is less favourable as the wall thicknesses increases.

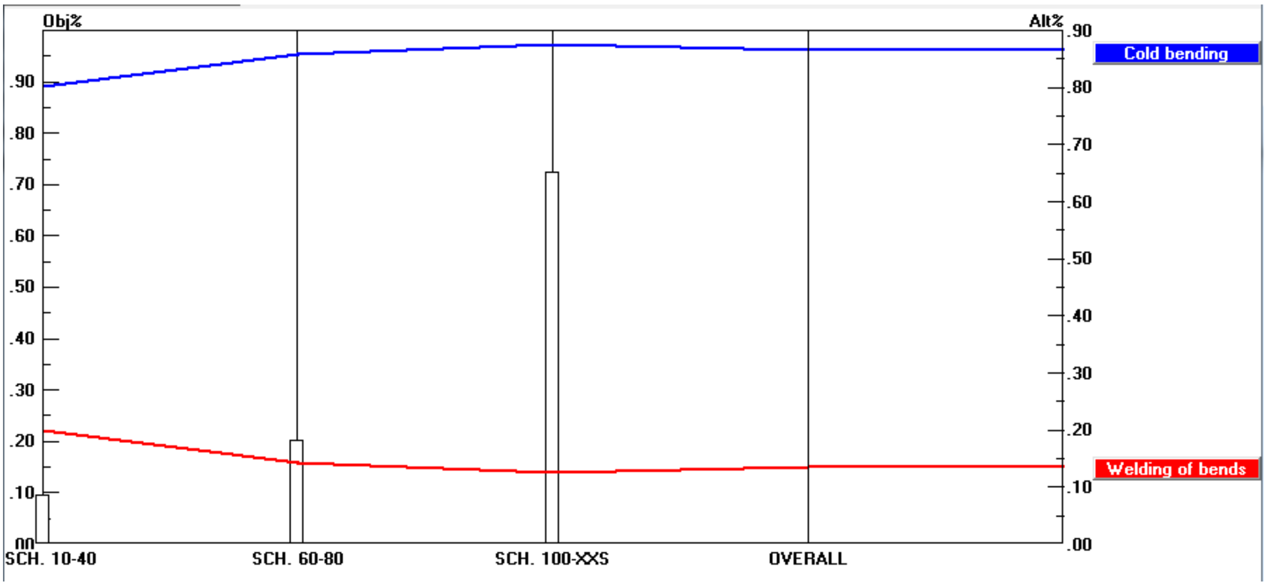

FIGURE 6-17: PERFORMANCE SENSITIVITY RESULTS OF DUPLEX, SUPER-DUPLEX BENDS WALL THICKNESSES WITH RESPECT TO FABRICATION TIME CRITERIA.

6.2.4 6MO

Head-to-Head sensitivity

Figure 6-18 shows how the two alternatives are compared to one another against the different wall thicknesses (sub-criteria). Cold bending is preferable since the horizontal bars is displayed towards the left, and most preferable for SCH 100-XXS.

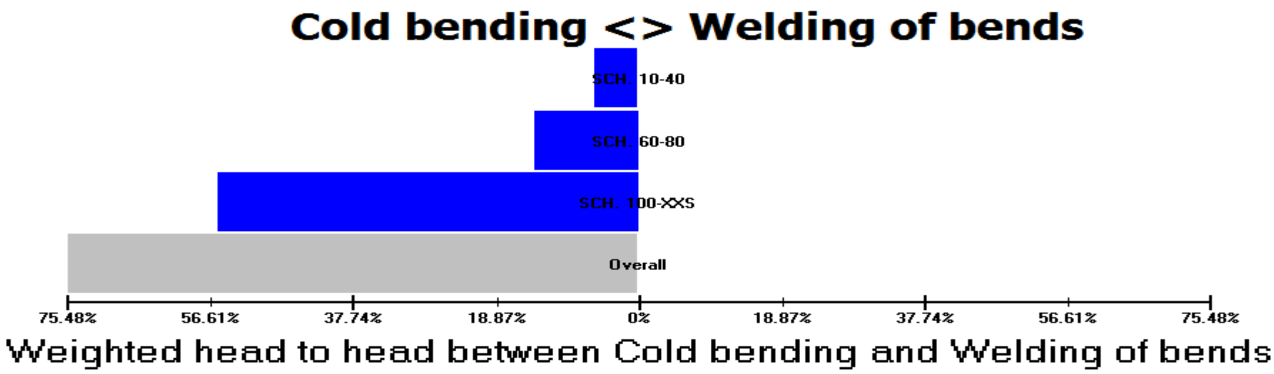

FIGURE 6-18: HEAD-TO-HEAD SENSITIVITY FOR 6MO BENDS. WALL THICKNESSES IN RELATION TO FABRICATION TIME.

Performance sensitivity

In Figure 6-19 and Figure 6-20 the performance graphs display how the two alternatives (cold bending and welding of bends) perform with respect to nominal pipe diameters and wall thicknesses as well as overall. On the left side y-axis, the sub-criteria priorities (Obj%) can be read, and on the right side of the y-axis the alternative priorities (Alt%) with respect to each sub-criterion can be read.

In both Figure 6-19 and Figure 6-20 cold bending is preferred more as the nominal pipe diameter and wall thicknesses (pipe schedules) increase. Figure 6-20 has a bit higher incline on the graphs than for the alternatives in Figure 6-19, meaning that the different wall thicknesses have a little bit more impact on the alternatives.

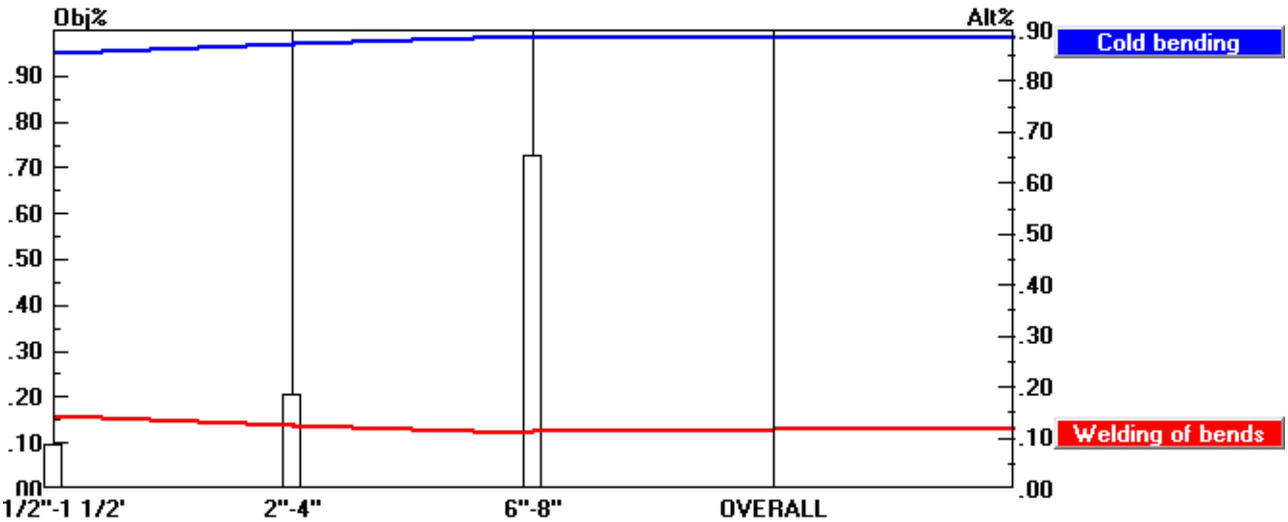

FIGURE 6-19: PERFORMANCE SENSITIVITY RESULTS OF 6MO BENDS NOMINAL PIPE DIAMETERS WITH RESPECT TO FABRICATION TIME.

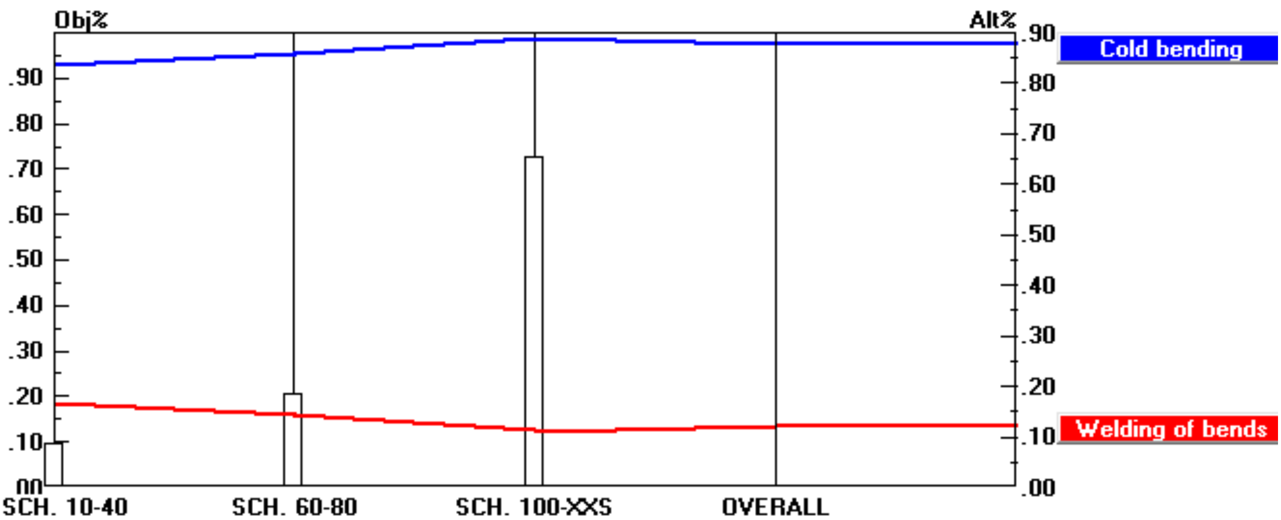

FIGURE 6-20: PERFORMANCE SENSITIVITY RESULTS OF 6MO BENDS WALL THICKNESSES WITH RESPECT TO FABRICATION TIME.

6.2.5 CMN STEELS: A106 GR. B AND API 5L GR. B

Dynamic sensitivity

Dynamic sensitivity analysis can be used to dynamically change the priorities of the objectives (i.e. criteria, sub-criteria) to see how these changes affect the priorities of the alternative choices (Expert Choice).

By dragging the objective's (i.e., material quality, fabrication cost and fabrication time) priorities back and forth in the left column the effect on alternative priorities will show in the right column.

In Figure 6-21 the sub-criteria (nominal pipe diameter) priorities with respect to its parent node (fabrication time) from pairwise comparisons are visualized in the left column, and the priorities of the two alternatives in the right column. Figure 6-22 illustrates how the priorities of the two alternatives change when the priorities of the objectives in the left column shift. In this scenario the priorities of the nominal pipe diameters 2''-4'' and ''-8'' were set to 0, causing the priority of ½''-1 ½'' increase up to 100%. As a result, the priority for cold bending decreases from 81,9% to 74,1% and the priority for welding of bends increases from 18,1% to 25,9%.

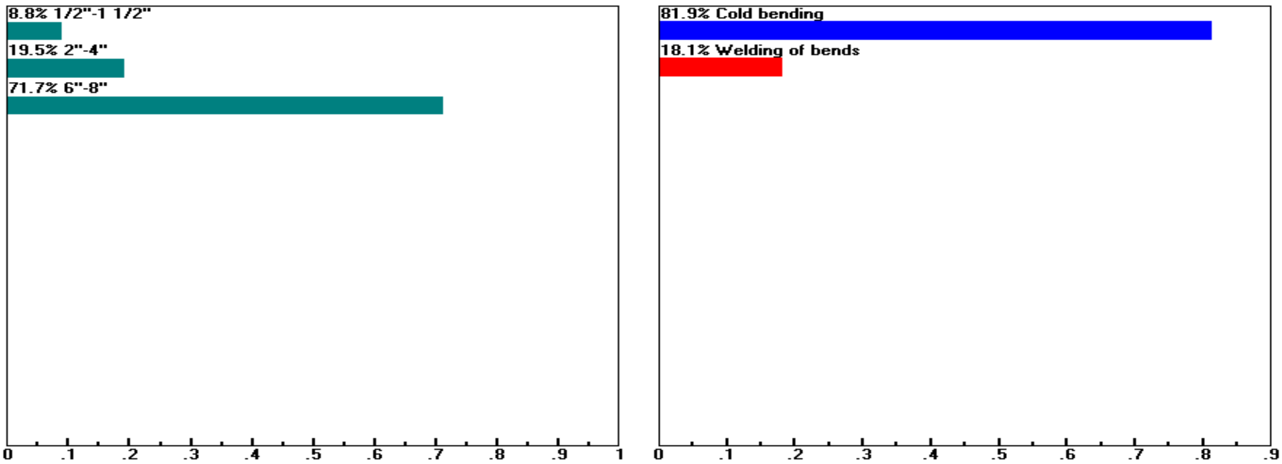

FIGURE 6-21: DYNAMIC SENSITIVITY FOR CMN STEELS NOMINAL PIPE DIAMETER WITH RESPECT TO FABRICATION TIME.

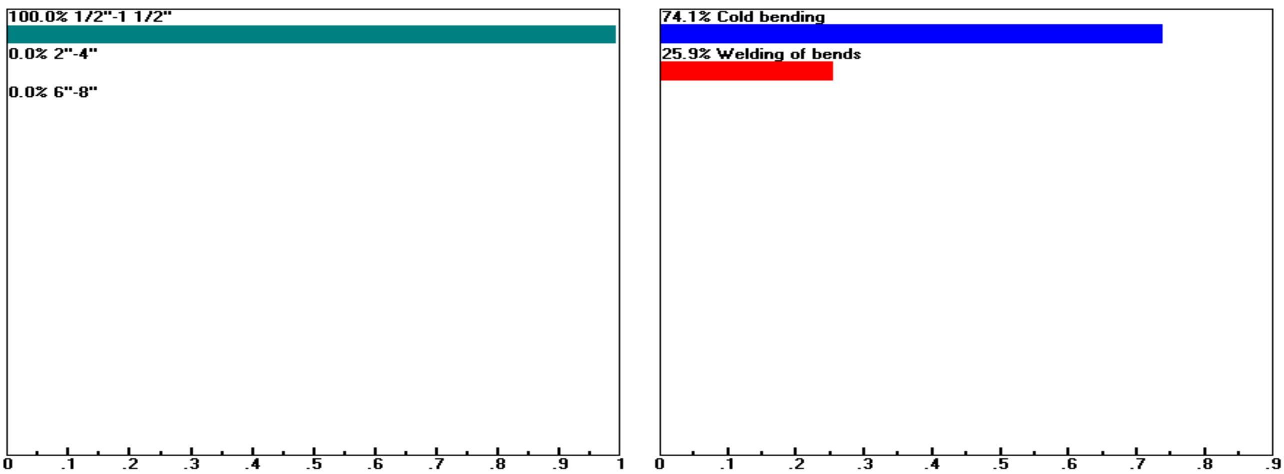

FIGURE 6-22: DYNAMIC SENSITIVITY, (CHANGED PRIORITIES) FOR CMN STEELS NOMINAL PIPE DIAMETER WITH RESPECT TO FABRICATION TIME.

Performance sensitivity

In Figure 6-23 and Figure 6-24 the performance graphs display how cold bending and welding of bends perform with respect to nominal pipe diameters (Figure 6-23) and wall thicknesses (Figure 6-24) as well as overall. On the left side y-axis, the sub-criteria priorities (Obj%) can be read, and on the right side of the y-axis the alternative priorities (Alt%) with respect to each sub-criterion can be read.

In Figure 6-23 the preference for cold bending increases as the nominal pipe diameter increases, it also shown that size 6''-8'' has the highest priority in relation to fabrication time (longest fabrication time to manufacture a CMn steel bent pipe).

It can be noted from Figure 6-24 that there is more difference in preference between cold bending and welding of bends from SCH. 10-40 to SCH. 60-80 than from SCH. 60-80 to SCH. 100-XXS. Overall cold bending has the highest preference based on criteria taken in consideration for the analysis.

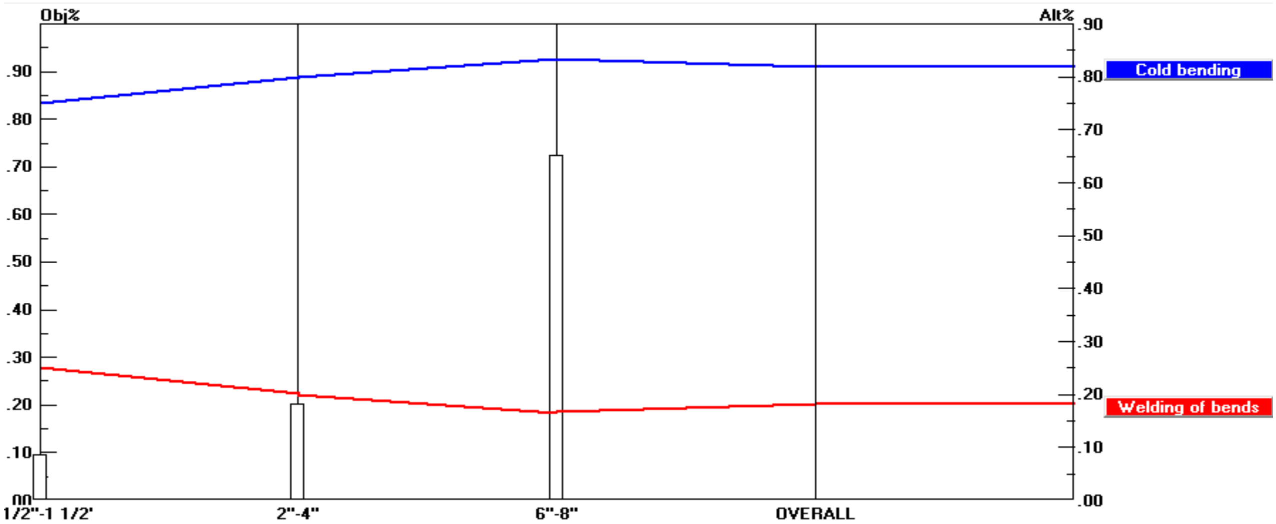

FIGURE 6-23: PERFORMANCE SENSITIVITY RESULTS OF CMN STEELS: A106 GR. B AND API 5L GR. B, NOMINAL PIPE DIAMETERS WITH RESPECT TO FABRICATION TIME.

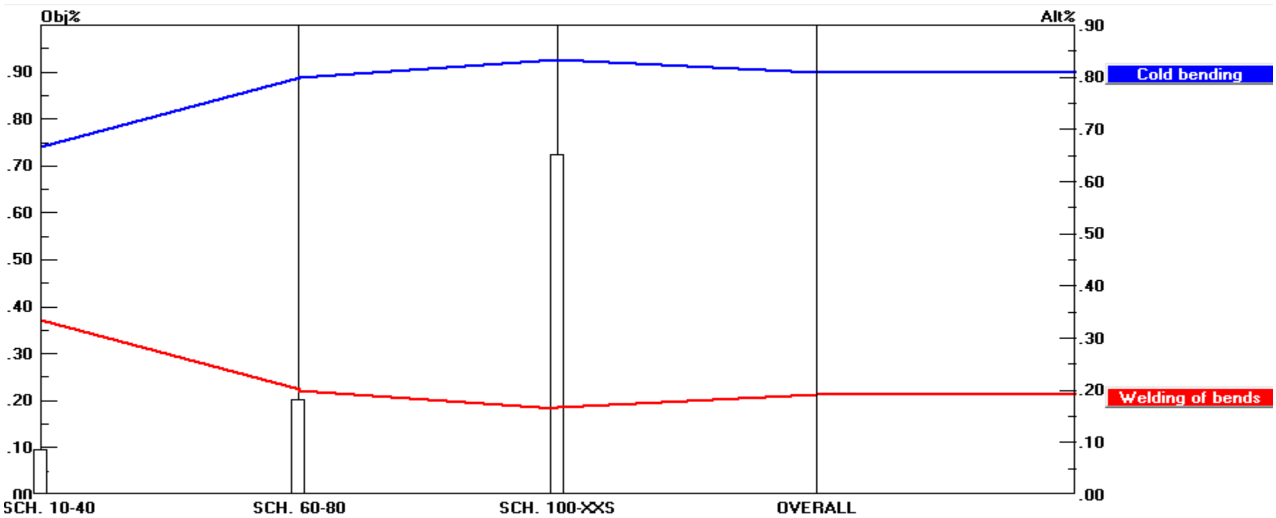

FIGURE 6-24: PERFORMANCE SENSITIVITY RESULTS OF CMN STEELS: A106 GR. B AND API 5L GR. B, WALL THICKNESSES WITH RESPECT TO FABRICATION TIME.

6.2.6 TP316

In Figure 6-25 and Figure 6-26 the performance graphs display how cold bending and welding of bends perform with respect to nominal pipe diameters (Figure 6-25) and wall thicknesses (Figure 6-26) as well as overall. On the left side y-axis, the sub-criteria priorities (Obj%) can be read, and on the right side of the y-axis the alternative priorities (Alt%) with respect to each sub-criterion can be read.

Overall, in both Figure 6-25 and in Figure 6-26 the preferences for the alternatives increase as the nominal pipe diameters and wall thicknesses (pipe schedules) increases. Also, the preferences for the objectives (nominal pipe diameters and wall thicknesses) with respect to fabrication time increases as the sizes of the objectives increases from left to right.

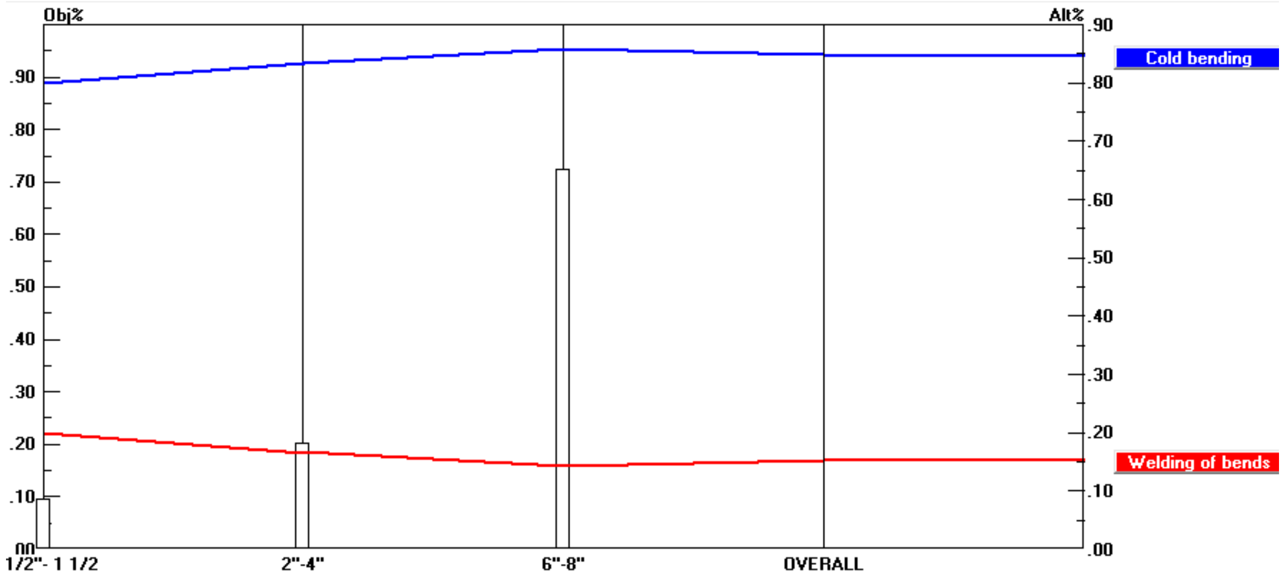

FIGURE 6-25: PERFORMANCE SENSITIVITY RESULTS OF 6MO BENDS NOMINAL PIPE DIAMETERS WITH RESPECT TO FABRICATION TIME.

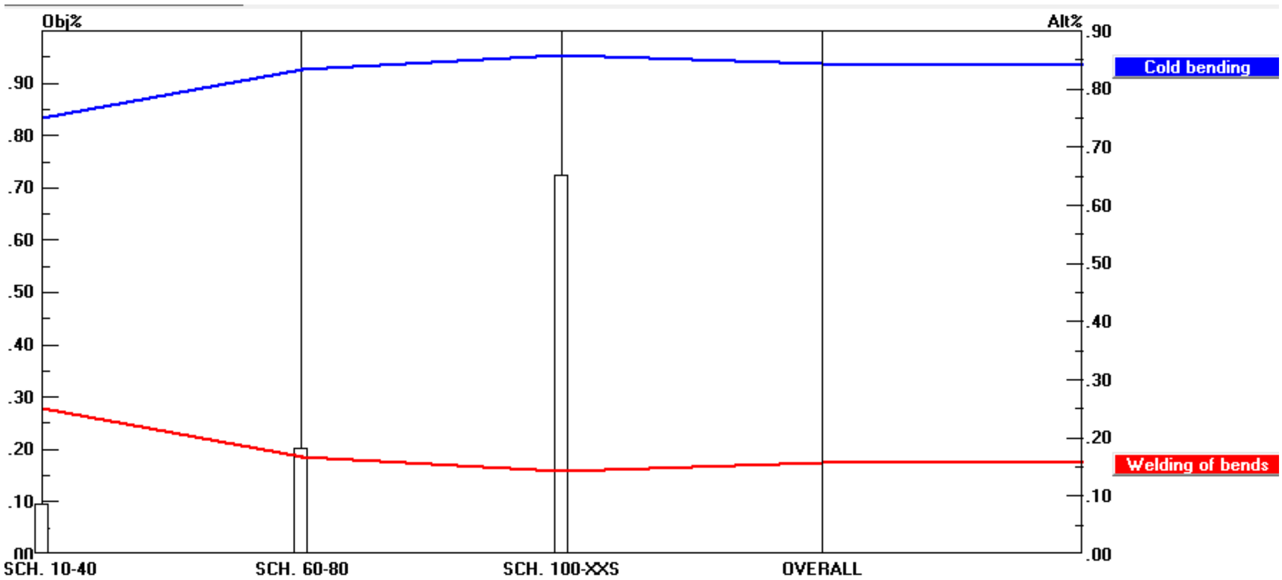

FIGURE 6-26: PERFORMANCE SENSITIVITY RESULTS OF TP316 BENDS WALL THICKNESSES WITH RESPECT TO FABRICATION TIME.

6.2.7 TITANIUM GR. 2

In Figure 6-27 and Figure 6-28 the performance graphs display how cold bending and welding of bends perform with respect to nominal pipe diameters (Figure 6-27) and wall thicknesses (Figure 6-28) as well as overall. On the left side y-axis, the sub-criteria priorities (Obj%) can be read, and on the right side of the y-axis the alternative priorities (Alt%) with respect to each sub-criterion can be read.

In Figure 6-27 there is barely any difference in preference between cold bending and welding of bends from ½'' -1 ½'' to 2''-4'', and from 2''-4'' to 6''-8'' the preference for the alternatives slightly changes. Note that 6''-8'' has a much higher priority in relation to fabrication time than ½''- 1 ½'' and 2''-4''.

Figure 6-28 show that the preferences for the alternative changes as the wall thicknesses increases (pipe schedules).

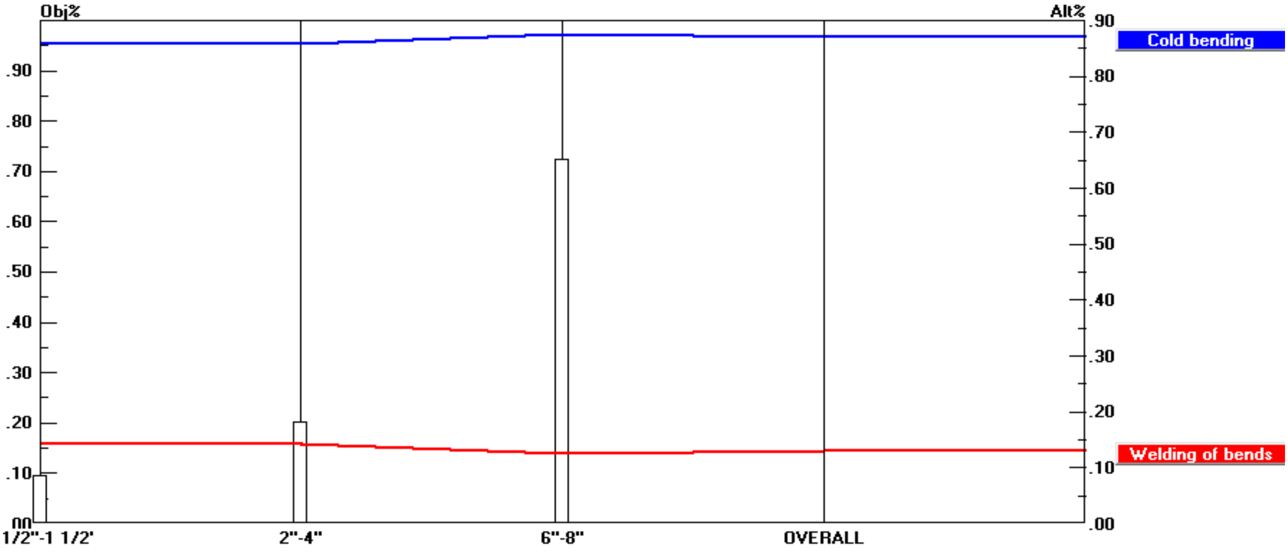

FIGURE 6-27: PERFORMANCE SENSITIVITY RESULTS OF TITANIUM GR. 2 BENDS NOMINAL PIPE DIAMETERS WITH RESPECT TO FABRICATION TIME.

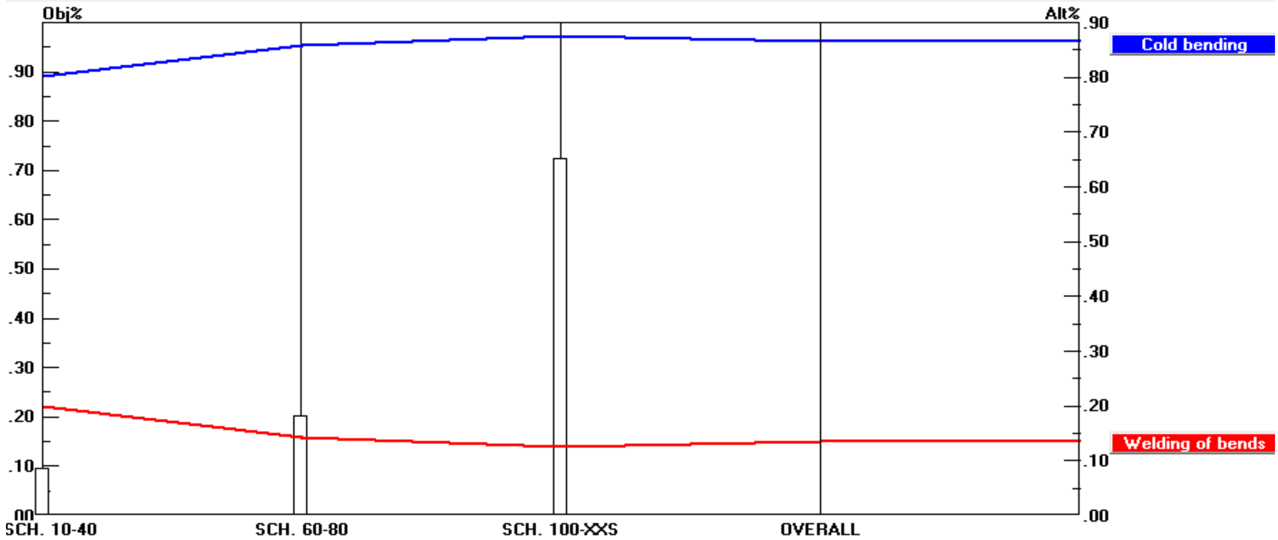

FIGURE 6-28: PERFORMANCE SENSITIVITY RESULTS OF TITANIUM GR. 2 BENDS WALL THICKNESSES WITH RESPECT TO FABRICATION TIME.

7 DISCUSSION AND CONCLUSION

As seen in the analysis in Ch. 5.2 and Ch. 6.2, cold bending has a lower cost per unit and fabrication time than welding of bends. It should be mentioned that this is without post bend heat treatment for cold bent pipes. The cost for cold bending will increase if heat treatment is required after bending. The main impact factors to cost per unit is less NDT and fabrication time, both favouring cold bending.

Mentioned in Ch. 3.1, cold bending does have some limitations which makes welding of bends more suitable in some areas. For instance, if the nominal pipe diameter is bigger than 8'' cold bending is not an option; induction bending is an option also in larger dimensions, but the method has not been taken into consideration in this thesis. It is important to note that some firms have additional requirements to cold bending as a method to fabricate bent pipes and do prohibit the method in some cases.

Analytic Hierarchy process (AHP)

AHP analysis can be a powerful method to compare different alternatives (different manufacturing techniques in this thesis) when used in the correct way. Firstly, the principles and background of AHP must be understood, then the hierarchy has to be established. As a newly introduced user to AHP there is always chances for incorrect calculation or mistakes. Several steps were taken to prevent incorrect calculations and results. The analysis was performed in Expert Choice software, it was also calculated in Excel to check that the results were similar.

Creating the hierarchy for the analysis took longer than expected. It was redesigned several times in the attempt to perform the most realistic and thorough analysis as possible. Note it is important that the designers of the analysis do not prefer one alternative over another, this can affect the outcome results.

The questionnaires developed to gather data for the analysis were conducted by several people with different types of experiences in the industry (ref. Ch.1.1.1). Overall, the inconsistency for the judgements in the questionnaires was 0,04 (below 0,1) which is consistent.

Saaty and Vargas explanation about rationality in AHP (Saaty and Vargas, 2001):

"*Rationality* is defined in the AHP as:

- Focusing on the goal of solving the problem;
- Knowledge enough about a problem to develop a thorough structure of relations and influences;
- Having enough knowledge and experience and access to knowledge and experience of others to assess the priority of influence and dominance (importance, preference or likelihood to the goal as appropriate) among the relations in the structure;
- Allowing for differences in opinion with an ability to develop a best compromise. "

With the criteria and sub-criteria given in the AHP analysis Figure 7-1 illustrates the overall synthesis results for all the five analyses. Cold bending as a manufacturing method to produce bent pipes has a higher preference than welding of bends in all the analysis.

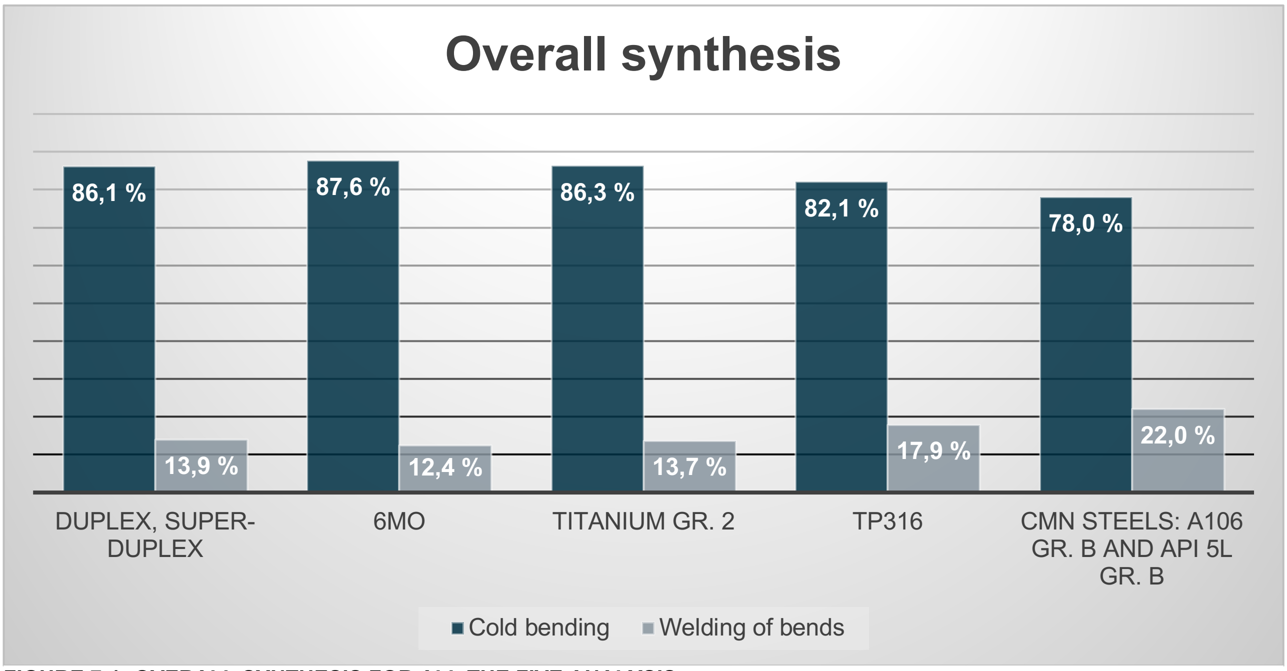

FIGURE 7-1: OVERALL SYNTHESIS FOR ALL THE FIVE ANALYSIS.

Based on calculations, analysis, interviews and literature, the results show that cold bending have benefits in several criteria and should be used where it is possible. The knowledge and access to choose cold bending as a manufacturing method could be improved, and then it may be easier to select this method. Some are sceptic and it would be of great interest if cold bending were more standardized in standards and requirements which is the case for welding of bends.

REFERENCES

AKER BP. 2020. *Hod* [Online]. Available: https://akerbp.com/project/hod/ [Accessed 09.03 2021].

ANTOSZ, K. & RATNAYAKE, R. M. C. 2019. Spare parts' criticality assessment and prioritization for enhancing manufacturing systems' availability and reliability. *Manufacturing Systems,* 50**,** 212-225.

ASKELAND, D. R., WRIGHT, W. J., BHATTACHARYA, D. K. & CHHABRA, R. P. 2016. *The science and engineering of materials,* Boston, Cengage Learning.

ASME. 2018. *B31.3 Process Piping* [Online]. Available: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=1055804 [Accessed 23.02 2021].

ASME. 2021. *About ASME* [Online]. Available: https://www.asme.org/about-asme [Accessed 14.05 2021].

ASTM. 2019a. *ASTM B861 Standard Specification for Titanium and Titanium Alloy Seamless Pipe* [Online]. Available: https://www.astm.org/Standards/B861.htm [Accessed 08.04 2021].

ASTM. 2019b. *ASTM B862 - Standard Specification for Titanium and Titanium Alloy Welded Pipe* [Online]. Available: https://www.astm.org/Standards/B862.htm [Accessed 06.04 2021].

CHIKALTHANKAR, S. B., BELURKAR, G. D. & NANDEDKAR, V. M. 2014. Factors Affecing on Springback in Sheet Metl Bending: A Review. 3. Available: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.676.6809&rep=rep1&type=pdf.

EUROPEAN STANDARD. 2017. *NS-EN 13480-4 Metallic industrial piping - Part 4: Fabrication and installation* [Online]. Available: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=934438 [Accessed 31.03 2021].

EXPERT CHOICE. *Expert Choice software* [Online]. [Accessed 22.04 2021].

MARKALI, J. 2019. *hydrogensulfid* [Online]. Available: https://snl.no/hydrogensulfid [Accessed 01.03 2021].

MATERIAL COST DATA 2020. Besparelse bøying HOD. *Confidential document from Aker Solutions*.

NORSOK. 2016. *M-601 Welding and inspection of piping* [Online]. Available: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=814500 [Accessed 23.02 2021].

NORSOK. 2020. *M-630 Material data sheets and element data sheets for piping* [Online]. Available: https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=1305207 [Accessed 02.02 2021].

NORWEGIAN PETROLEUM. 2021. *Exports of oil and gas* [Online]. Available: https://www.norskpetroleum.no/en/production-and-exports/exports-of-oil-and-gas/ [Accessed 06.04.2021].

OLJEDIREKTORATET. *HOD* [Online]. Available: https://factpages.npd.no/nb-no/field/pageview/all/43485 [Accessed 09.03 2021].

OLJEDIREKTORATET. 2020. *Produksjon* [Online]. Oljedirektoratet. Available: https://www.npd.no/fakta/produksjon/ [Accessed 03.02 2021].

SAMARAKOON, S. M. K. & RATNAYAKE, R. M. C. 2015. Strengthening, modification and repair techniques' prioritization for structural integrity control of ageing offshore structures. *Reliability Engineering and System Safety,* 135**,** 15-25.

STANDARDS NORWAY. 2019. *NORSOK standards* [Online]. Available: https://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standards/#.YJ46xy8ePRY [Accessed 14.05 2021].

SAATY, T. L. & VARGAS, L. G. 2001. *Models, methods, concepts & applications of the analytic hierarchy process,* Boston, Kluwer.

WEMAN, K. 2012. Welding processes handbook. 2nd ed. ed. Oxford ;,Philadelphia: Woodhead Pub.

APPENDICES

Appendix A: Excerpts from report regarding sour service testing of cold bent 22 and 25% Cr (duplex and super-duplex) pipe.

SINTEF

2018:00202 - Confidential

Report

Kværner PO 103193-1246-001, Valhall Flank West, SSC testing of 2xOD cold bent 22 and 25% Cr pipe.

Four-point bend (4PB) sour service testing of 2xOD cold bent 22% Cr duplex and 25% Cr super duplex 6" schedule 160 pipe according to ISO 15156-3.

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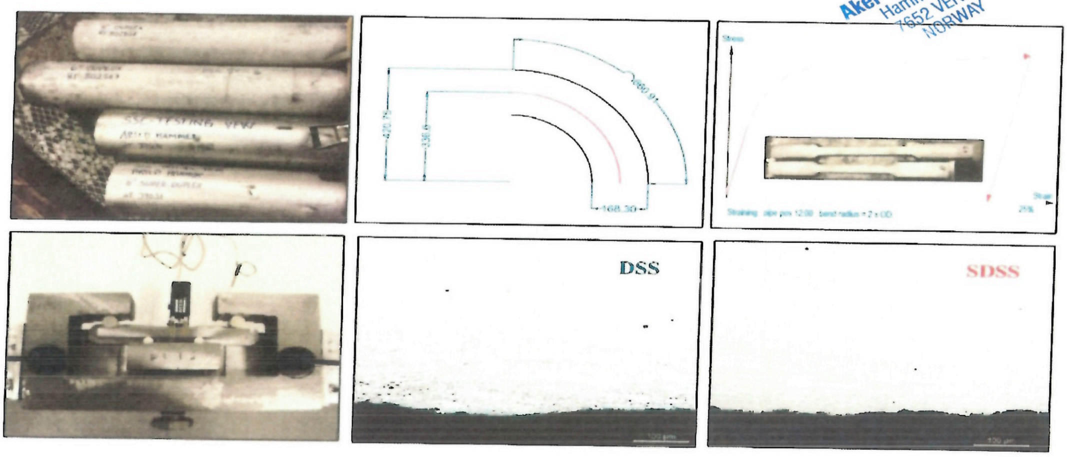

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KEYWORDS:
22% Cr, 25% Cr, DSS, SDSS, H2S, SSC, SCC, 4PB, cold bending

Report

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2018-02-16

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ABSTRACT

6" piping, schedule 160, made from UNS S31803 (22% Cr duplex stainless steel - DSS) and UNS S32760 (25% Cr super duplex stainless steel - SDSS) has been artificially cold bent by axial straining to 2xOD, i.e. a plastic deformation of approximately 25%. Then the process wetted side (inner pipe wall) was tested for sour service in simulated formation water (FW) and condensed water (CW) at room temperature (RT) and 90°C by use of the four-point bend (4PB) method. The test specimens were stressed by deflection to 80% of the AYS (elastic part) for the two materials in the strained condition at the actual test temperatures. The stressed side was in the "as delivered" condition and the materials were not artificially aged or re-passivated.

The FW contained 75000 mg/l of Cl^- + 500 mg/l of HCO_3^- and the CW contained 1 g/l of NaCl. The test gas consisted of 1.59 mole % H_2S in CO_2 and the total pressure was 5.13 barg at room temperature, i.e. P_{H2S} = 100 mbara and P_{CO2} = 6.0 bara. The "as mixed" final pH for the FW was measured to 5.26 and 5.29 at RT and 90°C, respectively. The "as mixed" pH for the CW was measured to 3.92 and 4.12 at RT and 90°C, respectively. The test period was 720 hours and the testing was performed in accordance with ISO 15156-3 and project clarifications.

The metallographic examinations of the tested materials showed **no signs of environmentally assisted cracking (like SSC/SCC) or corrosion** for any of the exposed specimens representing 2xOD cold bent 6" schedule 160 pipe of 22% Cr duplex and 25% Cr super duplex stainless steel.

Further testing with more aggressive conditions (and extended test time) is recommended to reveal application limits for these duplex materials in the cold bent condition. This is of special interest for the 22% Cr quality where the ISO defined limit for H_2S partial pressure is 100 mbara.

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Appendix B: Excerpts from report regarding sour service testing of cold bent 6Mo pipe.

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Report

Kværner PO PT-19-168, Sour service qualification testing of 2xOD cold bent 6Mo pipe

Four-point bend (4PB) sour service testing of artificially 2xOD cold bent (strained) 6" schedule 120, 6Mo (S31254) pipe at 1000 mbara H_2S according to ISO 15156-3

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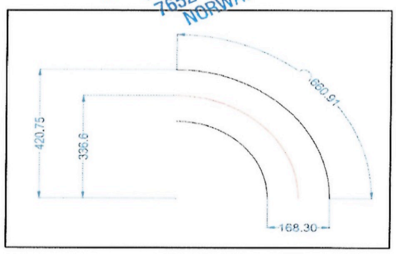

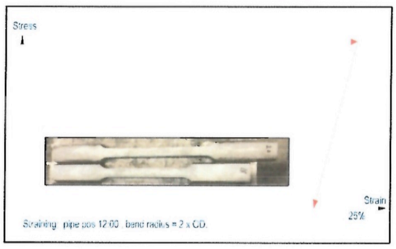

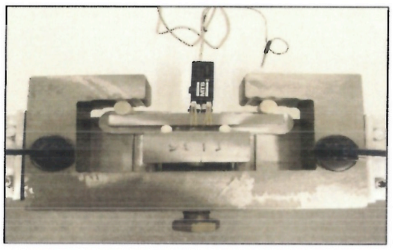

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Report

Kværner PO PT-19-168, Sour service qualification testing of 2xOD cold bent 6Mo pipe

Four-point bend (4PB) sour service testing of artificially 2xOD cold bent (strained) 6" schedule 120, 6Mo (S31254) pipe at 1000 mbara H2S according to ISO 15156-3

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ABSTRACT

Kværner provided 6" piping, schedule 120, made from UNS S31254 (6Mo) has been artificially cold bent by axial straining to 2xOD, i.e. a plastic deformation of approximately 25%. The inner pipe wall representing the process wetted side of the pipe was then tested for sour service in simulated formation water (FW) and condensed water (CW) at room temperature (RT) and 90°C by use of the four-point bend (4PB) method. The test specimens were stressed by deflection to 80% of the AYS (elastic part) for the two materials in the strained condition at the actual test temperatures. The stressed side was in the "as delivered" condition and the test material was not artificially aged or re-passivated.

The FW contained 75000 mg/l of Cl^- + 500 mg/l of HCO_3^- and the CW contained 1 g/l of NaCl. The test gas consisted of 16.21 mole% H_2S in CO_2 and the total pressure was 6.02 barg at RT, i.e. $\mathbf{P_{H2S} = 1000}$ **mbara** and $P_{CO2} \approx 5.0$ barg. The "as mixed" final pH for the FW was measured to 5.26 and 5.14 at RT and 90°C, respectively. The "as mixed" pH for the CW was measured to 3.92 and 4.11 at RT and 90°C, respectively. The test period was 720 hours. The testing was performed according to ISO 15156-3 and project clarifications.

The metallographic examinations of the tested materials showed **neither signs of sour service cracking like SSC/SCC nor corrosion** for any of the exposed specimens representing 2xOD cold bent 6" schedule 120 pipe of 6Mo (UNS S31254).

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