The Influence of Correct Transfer of Weld Information on Production Cost

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ABSTRACT

This study aims at identifying the causes for deviations between actual and theoretical weld weight. Previous performed studies have shown examples of up to 40% extra weld consumables used in some cases. One consequence is of course higher production cost but it can also give increased weight leading to higher fuel consumption and decreased payload. An interesting aspect is that generous margins on specific production measures dilute important feedback of process variation information preventing and prolonging structural root cause analysis.

The causes for the observed deviations can heritage from several areas, both technical and within the information handling. The investigation shows that single components of the information structure and system, such as unsuitable demands as well as incapable evaluation methods, significantly influences the reliability of the entire manufacturing process. The common factor concerning when problems occur, seems to be the ability of correct information transfer between different functions in the organisation preventing the mismatch to appear in the interface. Suggestions for improving this situation include cross functional agreements as well as new measuring methods.

Keywords: weight reduction, throat size, weld, demands, impression, measurement, information transfer, Six Sigma

1. INTRODUCTION

A large part of vehicle weight derives from the welded structures [1], hence playing an important role when striving for reduced fuel consumption per payload in relation to vehicle weight.

Global competition is driving the production towards shorter time to market, higher flexibility and decreased production costs, which lead to faster changes and new demands. The production of a welded component involves numerous functions within the company – from analysis and design to production and inspection. Customer demands and product, as well as production, information are constantly transformed, simplified and translated between these functions in the organization. This can, as this case study exemplifies, create serious mismatch leading to unnecessary costs and waste of production resources restraining the company's competitiveness.

Quality control in manufacturing companies has a long tradition. Ballou et al [2] states that many of the concepts and procedures can be applied to the problem of producing better quality information outputs, also seen as information products with information customers. Two reasons according to Daft and Lengel [3] for a company to process information are to reduce uncertainty (absence of information) and equivocality (lack of understanding) which affects the company's performance. Cohen and Levinthal [4] argue that the ability to recognize the value of information, assimilate and apply it is critical to the company's innovative ability. Also Kehoe et al [5] states that the effective use of information within manufacturing operations to support the decision-making processes, is a prime factor in the achievement of business goals. The company might have the information but lack methods of using it properly. Wheeler [6] emphasises the need of understanding of how to digest numbers to extract the knowledge that may be locked up inside the full range of the data, outliers included. Savage [7] and Deming [8] exemplifies that reasoning by comparing decisions-making based on average values instead of distribution and variation. The consequences show to be severe and affect the whole business.

To summarize the studied literature, the information handling is of great importance for the company's performance. By condensing the available data to e.g. average values only, a lot of the information is lost, which can have severe consequences for the precision and accuracy of the decision-making.

2. BACKGROUND

The companies involved are taking part in an on-going research project, WIQ – Weight reduction by Improved weld Quality, aiming towards reduced weight by improved weld quality. The weight reduction can be achieved by using thinner plates, but the demands on the welds will get higher because of increased material stress. Hence the importance of stable and predictable processes with known variation increases.

2.1. Specifications

Fillet welds are the most common weld type in the companies involved in the study. The size of a fillet weld is defined by throat size according to the two standards used at the companies [9, 10]. The actual shape of the weld surface could be straight, concave or convex as shown in Fig. 1 or even a combination of them.

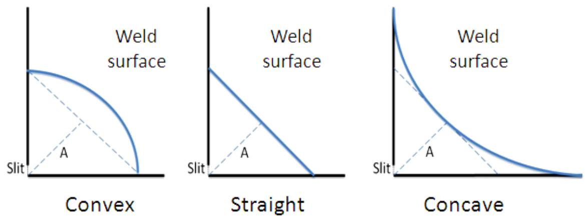

Fig. 1 Illustration of throat size A with convex, straight and concave weld shapes

A common specification used in the drawing, according to the standard [10] is shown in Fig. 2. VD is specifying the chosen weld class whereas i2 means penetration depth of 2 mm and a5 throat size of 5 mm.

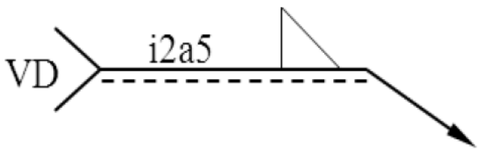

Fig. 2 Example of specification on the drawing.

2.2. Translating specifications into production data

The first site studied uses a process of converting specifications from the drawing into welding parameters used in the robot, containing several steps with numerous people involved. The process is currently not qualified according to any specific standard.

Specification: The demands stated on the drawings and in standards (created by the designer).

Preliminary Welding Procedure Specification pWPS: A preliminary document describing weld parameters for the tests to be performed by the robot programmer and production (created by weld coordinator).

Welding Procedure Approval Record WPAR: A report describing the results from the welded tests (made by weld lab analyst).

Welding Procedure Specification WPS: A document describing weld parameters to be used when programming based on the test results (created by weld coordinator).

Robot Library Parameters: A standardized parameter set based on the WPS (created by the robot programmer).

Actual Programmed Parameters: The actual parameters used in the robot program based on the robot library (created by the robot programmer).

The production personnel are then using the robot program to weld the parts. The parts are regularly audited by quality personnel.

2.3. Calculation of weld weight

Previous investigations within the companies had shown surprising results. A significant difference, more than 40% extra usage of welding consumables, between the theoretical and actual value was observed at some parts in two out of three sites. An example is shown in Fig. 3.

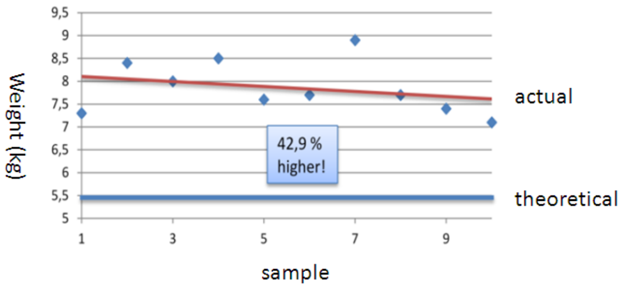

Fig. 3 Difference in weight between theoretical and actual

In the investigation the weight labelled as “theoretical” is calculated as:

$$W_{theoretical} = A_{theoretical} \cdot A_{theoretical} \cdot L \cdot \rho \quad (1)$$

where A is the throat size, L is the length of the weld and ρ is the density of the weld seam.

The extra weight in comparison with the total weight of the part is in the area of 0,5% and is not very influential in itself. The deviation in weld weight can however be seen as a symptom of lack of process control. As described earlier, stable, predictable processes is a necessary prerequisite to be able to reduce weight using thinner plates.

2.4. Influence on production cost

Apart from the influence of future development, the current production cost would also be affected by the described deviation in weld weight. An additional weld volume would generate the corresponding amount of extra consumables and hence cost. The extra production time could be even more serious. 20% extra weld volume means 20% extra time spent in the welding process during arc-on time - time, which instead could be spent on producing other parts. Yearly this means millions SEK in increased cost for this particular company. A higher order cost is the elusive and hard to estimate consequence of lack of feedback information for continuous process improvement.

2.5. Objective

The objective with the study was to increase the knowledge about the deviations in the process in order to facilitate improved process control. This can be exemplified by three questions:

- What is causing the deviation between theoretical and actual weld weight?
- Why is there a difference between sites?
- Does the transfer of process information affect the deviation?

3. METHOD

The method used was DMAIC – a Six Sigma methodology commonly described e.g. in [11]. The procedure guides the work into the phases Define, Measure, Analyse, Improve and Control. In the measure phase Measurement System Analysis (MSA) was an important tool to conclude if the precision of the measurement system is high enough to draw conclusions on process variation.

4. THE STUDY

The study included several sub sections inter alia identifying the weld weight distribution, measuring throat size, analysing the translation process from demand to weld and influence of gap. A comparison to another company was also performed.

4.1. Weld consumables distribution

The difference between actual and theoretical weld weight found in previous investigations initiated the study. During the study additional weight evaluations were performed to collect data about the chosen product. The used amount of consumables, i.e. the welding wire, can be detected by measuring the weight of the wire bin before and after welding. For lighter products the part itself can be weighed. The major part of the used amount of welding consumables will normally be distributed to:

- Throat size (the triangle shape)
- Gap (between the plates)
- Excess geometry (outside the triangle shape)
- Spatter, fumes (beside the part or in the air)
- Start/stop effects (e.g. wire in the wire liner to the robot)
- Difference from theoretical length
- Difference in density

The deposition efficiency- the weight of weld metal deposited in relation to the weight of electrode consumed – is one factor affecting the difference between the theoretical and actual consumption. The causes could include e.g. material being transferred into weld fumes instead of weld material. For solid wires that is generally said to be around 0,95-0,96 [12, 13]. This can be verified by weighing both the wire and the part before and after welding and note the difference between the results. Because of the precision of the scale used in the study this could neither be confirmed nor rejected. The measured deviation between weights of wire bins before and after welding compared to the part weight before and after welding could as well has been due to inaccurate scale readings. However it was concluded that spatter and fumes are not very significant in comparison to the other causes.

The amount of weld wire used during start and stop, e.g. to fill the wire liner, accounts for around 5% if it was to be performed for each part. This is however not the case but the wire in the liner is changed rather every 20th part. That means this contribution can be neglected.

The difference in length and density is also considered of minor importance in this study. Therefore a simplified model could be used for this purpose:

$$W_{bin,before} - W_{bin,after} = \\ = W_{throatsize} + W_{Gap} + W_{ExcessCS} \qquad (2)$$

where

$W_{bin,before}$	wire bin weight before welding
$W_{bin,after}$	wire bin weight after welding
$W_{throatsize}$	weld weight distributed in triangular part with actual throat size
W_{Gap}	weld weight in the gap between plates
$W_{ExcessCS}$	weld weight in the cross section outside the triangle that defines the throat size

For a constant amount of material added to a cross section, the presence of a gap will reduce the throat size and/or modify the contribution from the geometry term $W_{ExcessCS}$.

4.2. Measuring throat size using gauge

To be able to investigate which of the factors that have the most influence of the weight deviation the throat size needed to be measured. A MSA, measurement system analysis (gauge R&R), can be performed to see the repeatability and reproducibility of the measurement system. By doing so, the influence of both extrinsic factors (e.g. method and tool) and intrinsic factors (e.g. operator experience and motivation) will be investigated together as a system [14].

The commonly used tool for measuring throat size is a throat size gauge, of which an example is shown in Fig. 4.

Fig. 4 Throat size gauge.

The instructions for the usage differ. Depending on the weld shape, different scales are used for reading the result and the positioning of the tool arm is different as well. The variation of the method was investigated using MSA. The method showed not to be capable even with improvement of the process. The same result has previously been achieved by Hammersberg and Olsson [15]. An alternative evaluation method was developed and named WIA – Weld Impression Analysis- where a two-component polymer is applied to the outside of the weld as shown in Fig. 5. The impression is the cut and analysed. Further MSAs showed the measurement system to be both accurate as well as precise. The measurement system showed to be excellent for the investigated purpose and could therefore be used during the rest of the tests.

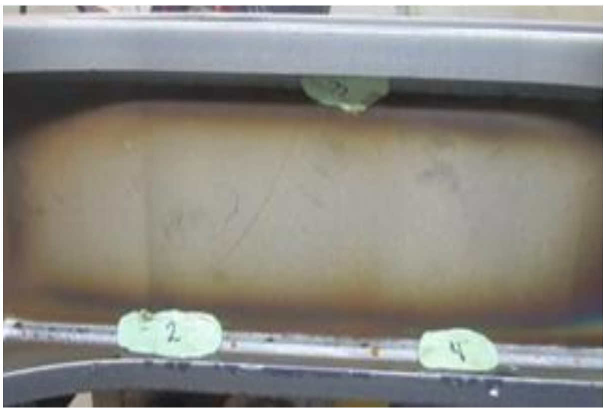

Fig. 5 Polymer applied to weld to get impressions.

4.3. Using WIA on a welded part

The WIA-method was chosen to be used for analysing actual welded parts. The samples were taken from weld seams based on their contribution to weld weight and their location on the frame. The samples were taken from weld seams that in sum constituted 15% of the theoretical weld weight of the part. Measurements were carried out on the same 16 spots on three equal parts. Two samples were collected per weld with the exception for one weld, where four samples were collected due to the curvature of the weld.

4.4. Analysis of translation process

To find out where in the process the added weight occurs, the following analyses were performed:

Firstly, the initial test samples based on the preliminary WPS (pWPS) were analysed extracting the resulting cross sectional area from existing documentation.

Secondly, the potential cross sectional area was computed from the WPS parameters for the welding wire feed and the welding speed in the welding direction, see equation 3 below.

Thirdly, the job description parameters for the welding robot were used for calculating the corresponding potential welding area, using the same equation.

Finally, data of weld parameters from the robot software was provided by the programmer and the corresponding potential cross sectional area was calculated.

When the wire feed speed WFS and the welding speed in the welding direction $V_{welding}$ are fixed, the potential of deposited cross sectional area is given by:

$$\left(Y_1 + Y_2\right)_{potential} = \frac{WFS * a_{wire}}{v_{welding}} \qquad (3)$$

The ratio of the two velocities is multiplied by a_{wire}: the cross section area of the welding wire. This assumes that all spill and evaporation are negligible, and that material is evenly distributed in the welding direction.

4.5. Influence of gaps

The compensation for gaps has been identified as a root cause of the weld weight deviation from the theoretical weight. The influence of gaps was investigated by setting up a series of experiments differing gap sizes with constant weld parameters to see how this affects the weld characteristics.

4.6. Comparison to site 2

A comparative study was performed at the site that had low deviation between theoretical and actual weld weight (almost 0%). Similar impression tests were performed and analysed using the WIA method.

Different organizational factors have been listed in Table 1 to compare the situation between the two sites investigated.

Table 1 Comparison structure between Site 1 and Site 2

	Site 1	Site 2
Demands	Lower specification limit only	Lower specification limit only
Weld shape	No general demand	Straight weld
WPS-process	Yes	No
Measuring method	Throat size gauge	Throat size corner gauge
Considered "normal" gap variation	0-3 mm	0-3 mm
Weld audit performed by	quality dep.	operator, technicians and manager.

5. RESULT

5.1. Result analysis of WIA samples

The analysis showed that all investigated welds were larger than specified. As Fig. 6 shows there is also a significant difference in excess cross sectional weld area between the A6 and the A5 type welds. It was found that A6 welding parameters had actually been used for the welds specified as A5 on the drawing.

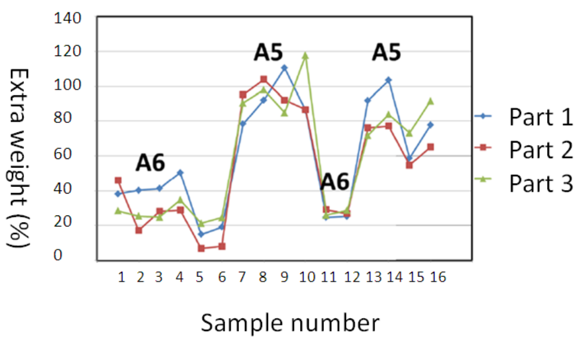

Fig. 6 Result of WIA investigation on four parts.

5.2. Result analysis of translation process

The different steps in the translation process were analysed. An example of the result for a5 sized welds with different wire feed speed can be seen in Fig. 7.

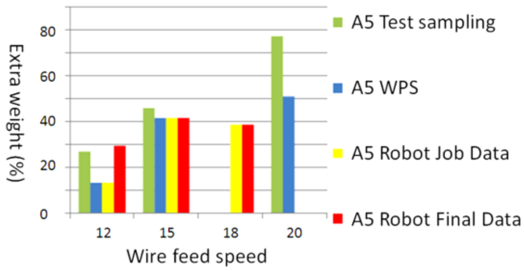

Fig. 7 Extra weight in the different process steps.

The investigation shows extra weight for all four wire feed speeds, often in the area 20-40% excess, on some occasions, even higher. The suggested extra weight from the WPS (blue bar in Fig. 7) is less than the extra weight in the test sampling record (green bar). The actual robot data (red bar) from the robot software is not always consistent with the robot job description (yellow bar).

The compensation creating a larger throat size is only a part of the deviation. The average contribution to total excess area can as previously be divided in material allocated inside the triangle formed by the throat size (Y1) and material allocated outside (Y2). On average only 41 % is directly linked with having a too big throat size as Fig.8 shows. Y2 is instead affected by for example weld angles and positions and none of the persons involved has mentioned any intentional choices of affecting this area.

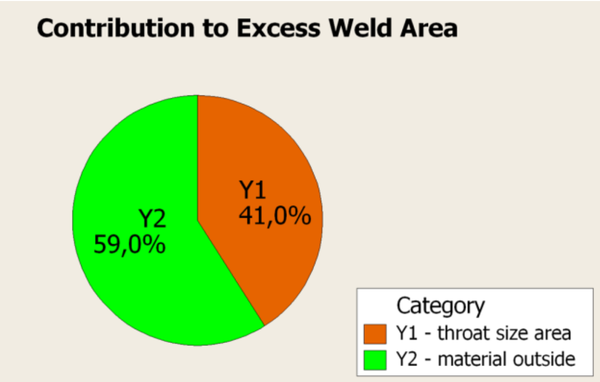

Fig. 8 Average contribution to excess weld area.

5.3. Result influence of gaps

The result from the test shifting the gap size is shown in Figure 9. The throat size is reduced as the gap increases, and also the range and variance of the throat size increases. This implies that higher gaps may not only generate smaller throat sizes but the resulting throat size is also subject to larger variance. For the red dots a root pass has been used thus the throat size should be slightly larger.

From this investigation an equation can be created which makes it possible to calculate the compensation needed for a certain gap variation.

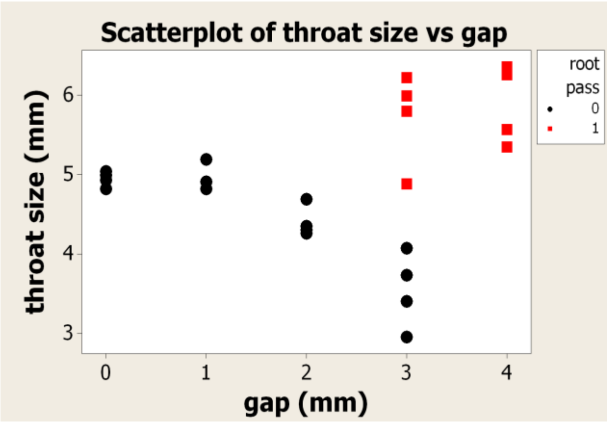

Fig. 9 Throat size vs gap.

5.4. Result comparison to site 2

The procedure for calculating theoretical weld weight differed between the sites. The theoretical value was in the case of site 2 obtained from a consumable table [12] where several factors were already accounted for. When using the same calculation procedure, the deviation between theoretical and actual value was 26%.

The result of the impressions showed a significant difference between the sites. Both the result from the weighing and the analysed impressions show that Site 2 adds less weld material (Table 2). The throat size is even less than the demands.

Table 2 Comparison results between Site 1 and Site 2

	Site 1	Site 2
Difference in weld weight part	+43%	+26%
Average % excess throat size area (Y1) in comparison to theoretical *in WIA samples*	111% of theoretical*	79% of theoretical
Average % total area (Y1+Y2) in comparison to theoretical *in WIA samples*	127% of theoretical*	104% of theoretical
Average throat size *in WIA samples*	107% of theoretical*	88% of theoretical

*Only a6 welds of sample considered

6. DISCUSSION

The reason for adding extra material seems to be compensation for possible gaps between plates. The investigation at Site 1 shows that the weld coordinator probably has increased welding speed based on inspection of the samples. The robot programmer has probably modified the parameters according to experience and/or special conditions when doing the robot job. Again, the robot programmer has made decisions to change it when it comes down to the actual robot program. Conclusively, these steps are not always coordinated in a strategic and consolidated fashion, leading to the reduction of process control.

As shown by the measurements, it is probable that a substantial part of the measured weld weight deviation from the theoretical value is facilitated by:

- The WPS is promoting a higher cross sectional area than the theoretical value by suggesting a lower weld speed.
- The robot software data is similarly promoting a higher cross sectional area by suggesting a lower weld speed.
- In some cases even robot jobs for other weld sizes than the specified was used.

The root cause of these deviations from the theoretical value is related to the human factor, and could be regarded as unintentional or intentional. The intentional part is to compensate for possible gaps according to both the responsible for the creation of WPS documents as well as the programmers.

At Site 2 the situation is different. There is no WPS-procedure or additional audit function similar to the one at Site 1 meaning less organizational interface. However, at Site 2 there instead seem to be a case of under compensation since none of the investigated samples reached the demand. The measuring method might also play a role in this case.

At a first glance this problem seemed to be about gaps. Gaps are of course of immense importance, especially the variation but when handling each case separately the solution does not seem very difficult. However, the organisation has a problem with the combined variation. The test samples vary as well as the WPS (which also has tolerance limits for the parameters). How the programmer then interprets and combines the WPS with other knowledge while programming varies significantly. The quality of the information that is transferred is being affected. These issues are abstract and more difficult to handle than only addressing the gap-problem.

The investigation shows some areas that could be the causes for mismatch:

The demands: How the demands are translated into specifications on the drawing is of course crucial. To only have a lower limit does not drive any activities towards decreasing the weight. This could create behaviour where a lot of safety margins are added in each step of the process. The choice of throat size as a measurement can itself lead to sub optimization since it can be questioned if it is the most suitable way to describe the weld. It has shown that other characteristics have a large impact on fatigue life e.g. described in [16].

The measuring method: The measurement system investigated added as much variation as the parts themselves to the measurement result. The demands only signals defect for a lower specification limit. The combination of unsuitable demands and the incapable measurement system creates a risk that over compensation has occurred. Site 2 had a different tool that was used for evaluating the throat size in categories (e.g. larger than throat size 5) rather than numerical values. A result from the study was a new, more precise and accurate, method called WIA for measuring the throat size as well as outer weld geometry using impressions. Using this method could limit some of the mismatch heritage from the measurement system.

Gap variation: The lack of knowledge about the present situation and possibility to address the problem in financial terms made it difficult to accurately account for gaps. An equation was created that could be used for predicting the amount of extra weld consumables and welding time necessary for achieving the wanted result in the current production situation. If it is necessary to be able to handle a gap variation between 0 and 2 mm it means a certain percentage of consumables needs to be added in order to achieve the target throat size. This means longer welding time and increased consumable usage which can be easily converted to cost. By doing so, a way to communicate the consequences of gap variation in financial terms has been created. That makes it possible to actively analyze and decide if compensation should be done or if the variation of the causing parameters should be reduced instead.

Structured compensation: Some of the compensation was done intentionally, other unintentionally. It seems like several functions tries to compensate e.g. for gaps without having all the facts. Some functions are also making compensations that are already done by another function. This situation does not exist at site 2 since the WPS process is not used and therefore contains less organizational steps. An additional point is that the large uncertainty in the measurement system using a gauge to determine actual throat size can be identified as root cause for some of the over compensation for potential gaps.

All in all several of the mentioned factors comes down to how the *information* is handled, meaning if the data is presented in such a way that it is possible to use it for making decisions. There seems to be a need for customized information for different functions. Such a system can include the identification of the internal customer for the information, how the data needs to be presented for each customer, what method should be used to get the information etc. [17].

As this study has shown there is a great potential in this area; short term when it comes to production cost but also long term considering it being a prerequisite for taking new leaps in product and process development.

The problem does not necessarily lies in technical issues but rather in how information is transferred and used. Therefore the cost for changing the situation could be very low, however not always very easy to implement. The solution needs to be cross functional since there are several functions involved in the entire process from demand to welded product. A common "language" all functions understand in the company is cost, hence it could be necessary to translate other measurements into that.

Therefore it is suggested to:

- Use a cross functional team when defining demands
- Define the cost for the particular demands based on design of experiments and use during the demand setting process and purchasing
- Investigate the current situation e.g. gap sizes necessary to compensate for
- Define where in the process the compensations should occur.
- Perform continuous follow-up using WIA to gain more knowledge about the process capability
- Plot the data in a control chart in order to get a signal if the process is drifting or any assignable causes occur

7. SUGGESTIONS FOR FURTHER WORK

The material allocated outside the triangle formed by the throat size has a great influence on the total excess area. Depending on the fatigue loads it is sometimes critical to have a smooth transition between the weld material and the plate. This is among other parameters controlled by changing weld positions and weld angles. Hence it would be of interest to investigate e.g. the connection between weld positions, weld angles and the excess geometry. By doing so it would be possible to state financially how much the suggested demand costs compared to lower demands.

The variation of gaps seems to be very influential, at least since it is compensated for in many steps. A study to investigate the current gap situation would be of interest in order to base the compensation-decision on facts.

Site 2 used another type of measuring device. It would be of interest to see its reliability and repeatability for its purpose.

8. CONCLUSIONS

The case study demonstrates consequences of communication mismatch leading to increased production costs as well as long term effects on development.

The most influential parameters on the deviation between theoretical and actual weld wire consumption are gap, excess throat size shape of weld and excess geometry outside the throat size triangle.

The information handling seemed to be one important root cause. To a large extent it comes down to lack of communication between different functions. Several influential factors were highlighted such as demand setting, used evaluation methods and structure of the compensation processes.

When converting e.g. the consequences of gap variation to cost, a way to communicate in financial terms has been created. That makes it possible to actively analyze and decide if compensation should be done or if instead the variation of the causing parameters should be reduced. That means, the right quality information actually not only affects the short term costs but also facilitates strategic development.

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10. REFERENCES

[1] Samuelsson, J., B. Jonsson and Z. Barsoum (2008). Service fatigue design of complex welded construction equipment, *Materialwissenschaft und Werkstofftechnik*, **39**, 734-739.

[2] Ballou, D., R. Wang, H. Pazer and G Kumar.Tayi (1998). Modeling Information Manufacturing Systems to Determine Information Product Quality, *Management Science*, **44**, 462-484.

[3] Daft, R.L. and R.H Lengel (1986). Organizational Information Requirements, Media Richness and Structural Design, *Management Science*, **32**, 554-571.

[4] Cohen, W.M. and D.A. Levinthal (1990). Absorptive Capacity: A New Perspective on Learning and Innovation, *Administrative Science Quarterly*, **35**, 128-152.

[5] Kehoe, D.F., D. Littke and A.C. Lyons (1992). Measuring a company IQ, In *Third International Conference on Factory 2000 - Competitive Performance Through Advanced Technology*, London, England, pp 173-178.

[6] Wheeler, D. (2000). *Understanding Variation The Key to Managing Chaos*, SPC Press: Knoxville USA, p 162.

[7] Savage, S. (2002). The Flaw of Averages, *Harvard Business Review*, 20-22.

[8] Deming, E. (1994). *The New Economics for Industry, Government, Education*, MIT: Cambridge USA.

[9] Swedish Standard (2004). *SS-EN ISO 5817 Welding-fusion-welded joints in steel, quality levels for imperfections*.

[10] Volvo Group (2011). *STD 181-0004 Fusion welding - Weld classes and requirements life optimized welded structures steel, thickness ≥ 3mm*, Volvo Group, pp 14.

[11] Magnusson, K., D. Kroslid D. and B. Bergman (2003). *Six Sigma The Pragmatic Approach*, Studentlitteratur: Lund, p 478.

[12] ESAB. *ESAB Svetshandbok. Tillsatsmaterial för olika grundmaterial*, Göteborg.

[13] Elga (1997). *Welding Consumables*, Partille.

[14] Dickens, J.R. and D.E. Bray (1994). Human Performance Considerations in Nondestructive Testing, *Materials Evaluation*, 1033-1041.

[15] Hammersberg, P. and H Olsson (2010). Statistical evaluation of welding quality in production, In *the Swedish Conference on Light Weight Optimized Welded Structures*, Borlänge, pp 148-162.

[16] Barsoum, Z. and B Jonsson (2011). Influence of weld quality on the fatigue strength in seam welds, *Engineering Failure Analysis*, **18**, 971-979.

[17] Öberg, A., P. Hammersberg, L-E Svensson (2012). Selection of Evaluation Methods for New Weld Demands: Pitfalls and Possible Solutions, In *18th World Conference on Nondestructive Testing*, Durban.