VariLight

Reduced VARIation in the manufacturing processes enabling LIGHTweight welded structures

Public report

Project within Hållbar produktion

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Content

1. Summary

In VariLight weld quality, cut edges, and load estimation were studied in order to identify the sources of variation, affecting the durability performance of fatigue loaded structures. The main target was to enable control of the variations in production and load estimation in order to increase productivity and enable development towards lightweight welded structures with accurate safety margins and failure probability rates according to the Load-Strength model. The effect of this will be reduced environmental impact, reduced lead time, and increased productivity. The work was based on results and recommendations from previously funded FFI projects; LOST, WIQ and LightStruct. The project work was conducted in seven workpackages of which WP7 was connecting the work in WP2-6 to get a holistic view.

2. Sammanfattning på svenska

VariLights syfte är att möjliggöra viktreducering av svetsade strukturer för att på så sätt minska miljöpåverkan, reducerad ledtid och förbättra produktiviteten. Viktreduceringen kan uppnås genom att förstå och kontrollera spridningen i produktion och beräkning och på så sätt möjliggöra exaktare säkerhetsmarginaler.

I VariLight inkluderades hela kedjan från kundens användande, konstruktion och beräkning, till produktion och mätning för att identifiera de variationskällor som påverkar hållfastheten för utmattningsbelastade strukturer. Arbetet baserades på resultat och rekommendationer från tidigare finansierade FFI-projekt; LOST, WIQ och LightStruct. Projektarbetet genomfördes i sju arbetspaket varav WP7 knyter ihop arbetet i WP2-6 och därmed skapar en helhetssyn.

Projektet har ökat förståelsen för variation i varje steg i processen och på vilken hierarkisk nivå de adresseras; från kundanvändning och design till tillverkning, testning och användning. Att skapa medvetenhet och ett gemensamt språk är det första steget mot att göra rätt åtgärder, av rätt roller och på rätt organisatorisk nivå för att mildra effekten av variation. Projektet har tagit en helhetssyn genom arbetspaket 7 för att hjälpa organisationen att uppnå bästa totaleffekt.

Målen för VariLight har varit att:

- Studera och kartlägga variationskällorna i beräkning, konstruktion, tillverkning, provning, mätning, visualisering och kommunikation samt identifiera möjligheterna att minska dem utifrån ett helhetsperspektiv
- Öka kunskapen om lokal svetsgeometri, restspänningar och deras relaxering för mer exakta livlängdskalkyler
- Utveckla rekommendationer och riktlinjer för tillverkningsprocesser och designförfaranden med större noggrannhet och minskad variation

- Möjliggöra ytterligare introduktion av vikt-till-styrka-effektivt material i svetsade strukturer utan att öka risken för haverier

De olika arbetspaketen har kartlagt nuvarande variation i respektive steg i processen och identifierat möjliga åtgärder och riktlinjer i enlighet med projektmålen. För att säkerställa att deltagarnas förväntade projektresultat blev uppfyllda genomfördes en workshop för att identifiera dessa. Uppföljning mot de förväntade projektresultaten skedde kontinuerligt.

Projektet levererade önskat resultat enligt impact-kategorierna:

- **Instrumentellt:** Utifrån demonstratorer framtagna rekommendationer för livslängdsberäkning, LCA, restspänningar, förbättringsmetoder, mätetal, skärprocesser och sprickinitiering. Modell för variationshierarki, informationshantering och visualisering togs fram.
- **Konceptuellt:** 13 akademiska publikationer och examensarbeten
- **Kapacitetsbyggande:** Utbildningar, filmer, handbok och presentationer
- **Kulturellt:** Förändrat synsätt inom organisationerna
- **Varaktigt deltagande:** Stärkt nätverk och uttalad önskad om fortsatt forskning

3. Background

Welded structures in heavy machinery are subjected to fatigue loads. There is however a variation both in load among customers as well in strength. Failures occur when high load intensity meets a week component. The loading situations are determined by the customer, but the fatigue strength is formed in production. The failure rate is determined by the amount of overlap of the load and strength distributions. A decreased variation of the strength would lead to a lower failure rate even though the median strength is unchanged.

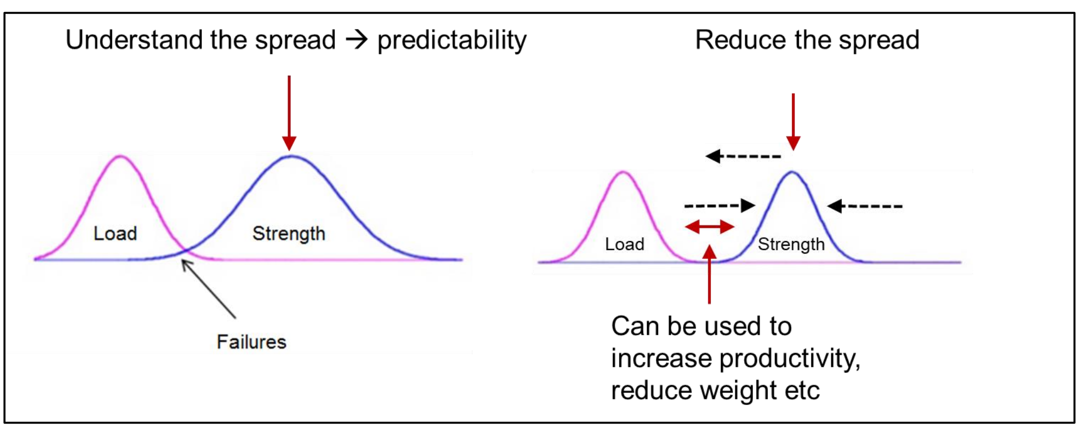

Figure 1: Load-strength distributions affecting failure rate.

Previous research has shown that there is often unknown variation in all stages of manufacturing, from load estimation to final assessment of the product. To avoid failures this uncertainty is handled by adding safety margins in all stages of manufacturing, thus increasing weight and cost. Those safety margins influence productivity, lead time, and business flexibility because products are over-processed. Perhaps even more influential is the effect these uncertainties have on the implementation of design solutions enabling light weight structures.

Light weight structures reduce the environmental impact by reduced fuel consumption, increased load capacity, and reduced material and energy usage. By understanding the variation in all stages of manufacturing, there is a possibility to reduce safety margins, hence enabling weight reduction without increasing the risk of failures. Therefore, understanding and possibly reducing the variation will affect environmental impact, productivity, lead time, and business flexibility of welding companies.

Previous and currently running FFI project which are related to VariLight where several participants are involved, focus on the introduction of High Strength Steel (HSS) and lightweight structures. In the National Technology Platform for Lightweight Welded Structures, LOST (VINNOVA) several important industrial and academic results were developed. Some of the findings in LOST as the new weld quality system are refined for serial production in the FFI project WIQ (Weight reduction by Improved weld Quality). In the FFI project LightStruct (LIGHT-weight high performance welded STRUCTures) the aim was to investigate new hybrid welding processes for highly fatigue loaded structures. In the FFI project Onweld (ON-line method for quality assurance of WELDed structures) development of technologies and algorithms for local weld geometry measurements for quality assurance (ONWELD) were developed and implemented in production environment.

In the research project, VariLight, the variation in weld quality, cut edges, and load estimation were studied in order to identify the sources of variation which affect the durability performance of fatigue loaded structures. The objective is to enable control of the variation in production and the load estimation in order to develop lightweight welded structures with accurate safety margins and failure probability rates and thereby reduce environmental impact and lead time while increasing productivity and business flexibility.

4. Purpose, research questions and method

The purpose of VariLight is to enable weight reduction of welded structures which are subjected to fatigue in order to reduce the environmental impact and improve productivity. This is achieved by studying and mapping the sources of variation and determine possibilities to reduce them in manufacturing processes (welding and cutting), structure strength, and load estimation. An additional purpose is to develop operating competence for the Swedish welding industry and influence education.

The research has been conducted by answering the following research questions:

RQ 1: What is the current situation regarding variation in load estimation, analysis of residual stresses, cut edges, and fabrication?
RQ 2: How can the negative effect of the variation identified be mitigated?
RQ 3: How should initiatives to reduce variation be prioritized from a holistic point of view to gain the best overall effect?

The research has been conducted in seven workpackages.

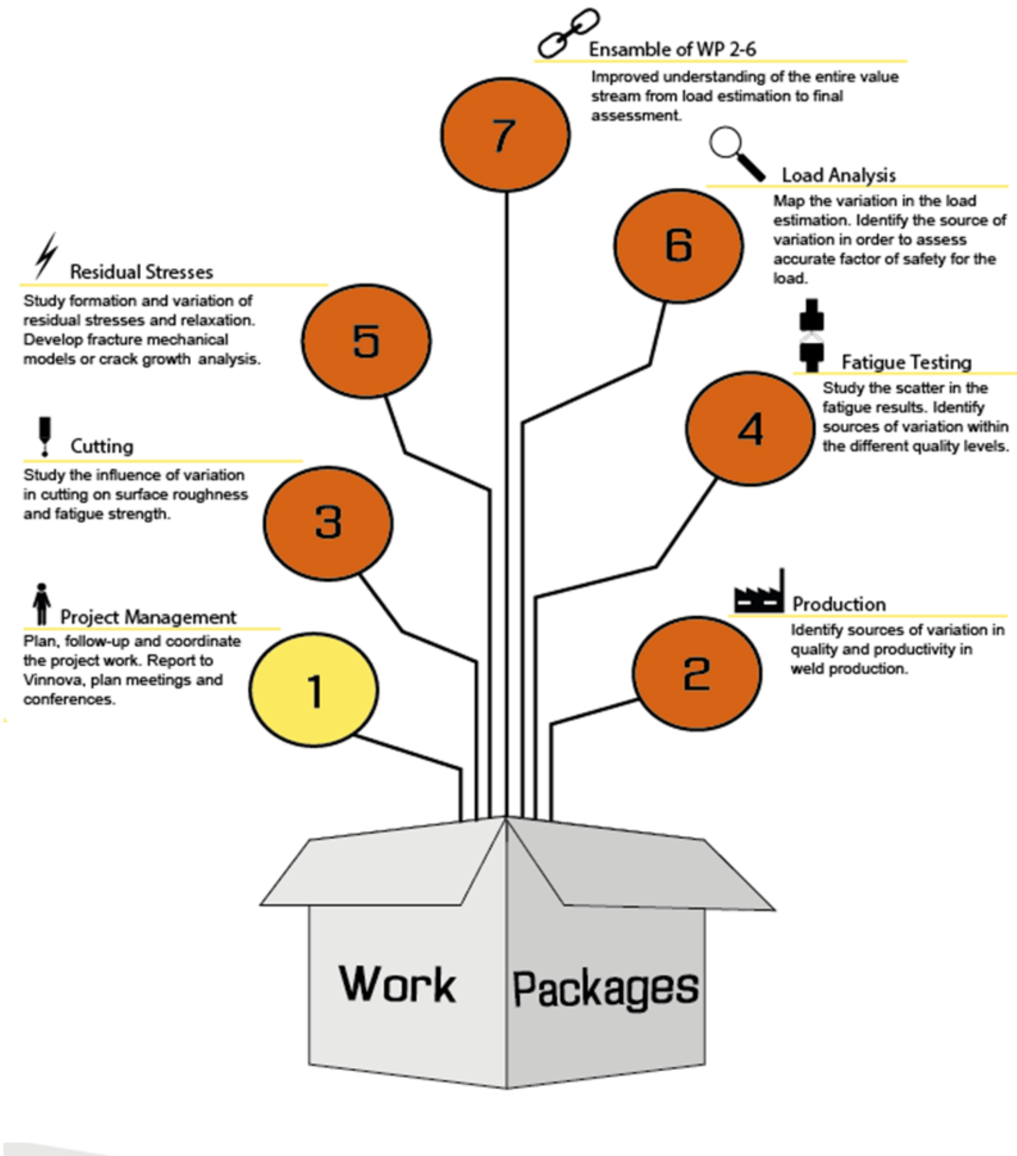

Figure 2: The project work was divided into seven workpackages.

5. Objective

The objectives for VariLight have been to:

- Study and map the sources of variation and possibilities to reduce them with a holistic approach in design and manufacturing processes (welding and cutting), structure strength and load estimation.
- Increase the knowledge of local weld geometry, welding residual stresses, and their relaxation during loading for more accurate life estimations.
- Develop recommendations and guidelines for manufacturing processes and design procedures with higher precsision and reduced variation.
- Enable further introduction of more weight-to-strength efficient material in welded structures without increasing the risk for failures (target of 20 % weight reduction).

6. Results and deliverables

The work packages have mapped the current variation in each step of the process and identified possible measures and guidelines in accordance with the project objectives. In order to ensure that the participants' expected project results were met, a workshop was conducted to identify them. Follow-up against the expected project results was done continuously.

The project delivered the desired result according to the impact categories:

- **Instrumental:** Based on demonstrators, recommendations for lifetime estimation, LCA, residual stresses, improvement methods, measurements, cutting processes and crack initiation are developed. Models for variation hierarchy, information management and visualization created.
- **Conceptual:** 13 academic publications and master thesis works
- **Capacity building:** Training, movies, a handbook and presentations
- **Cultural:** Changed approaches within the organizations
- **Enduring connectivity:** Strengthened network and expressed desire to continue the collaboration in future research

The project has worked actively to identify and deliver results to both academia and industry and has involved many students from different universities, even outside the project constellation. The results and deliverables are further described for each work package.

6.1 WP1 Project Management

The project has had 30 scheduled joint project meetings via Skype and 10 meetings face to face. The project has shared information and material on a common platform. There have also been regular steering committee meetings to secure the direction and deliverables of the project. In the start of the project a workshop was facilitated to scope the research as well as to create a common language and understanding of the topic. The workshop tried to answer the question “What are the largest problems predicting and understanding factors influencing field life time?”. The common answer was “The uncertainty of the product usage and lack of common view and cross-functional implementation success preventing us from understanding the influencing factors’ importance and interactions to life time”. That became the basis for the work.

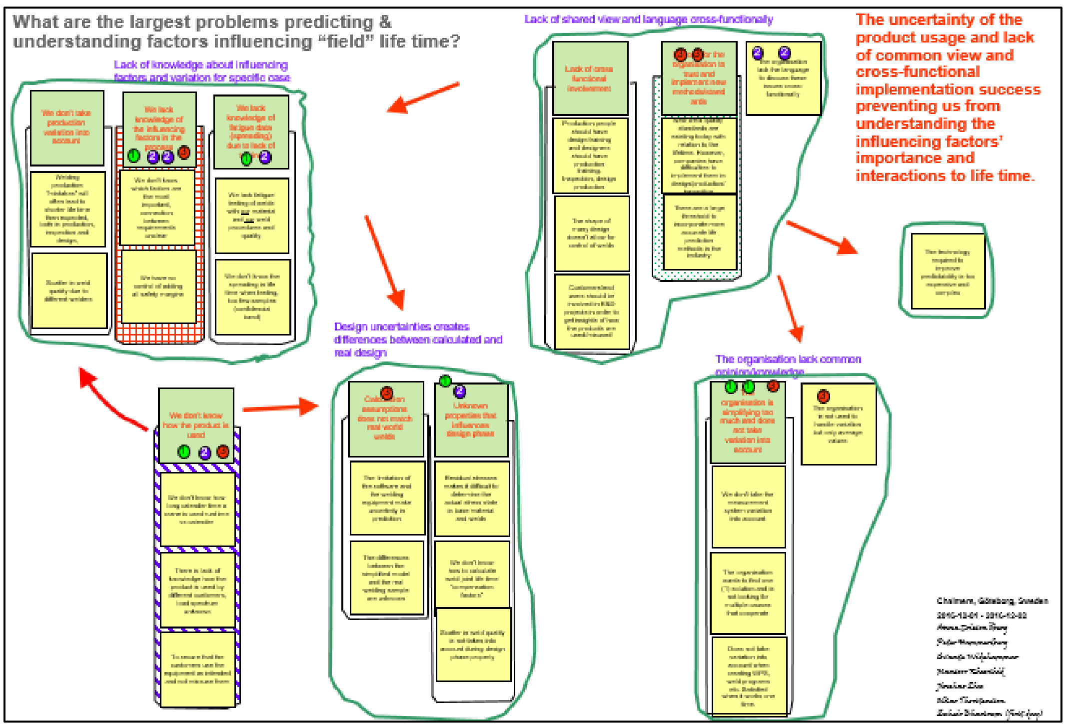

Figure 3: The AIM-workshop in the beginning of the project.

Different types of impact are important for the project participants (based on Scholarship with Impact by Pettigrew, A. M. 2011):

- Instrumental impacts: tangible products or services
- Conceptual impacts: scholarly contribution
- Capacity-building impacts: training and collaborative activities
- Cultural changes: achieved in the organizations
- Enduring connectivity impacts: knowledge exchange activities and relationships

How to increase the impact of industry- academia collaboration through co-production was described in a journal paper as well as in a handbook. To ensure to capture the different dimensions of impact a collaborative workshop was conducted, based on the affinity and interrelationship method, identifying what academia and industry require as result from the projects. The participants from the companies as well as universities noted on post-its what they wanted as a result from the project. The notes were at first divided into industry and academia. They were further clustered and were assigned a descriptive heading. The headings from the grouped notes from academia and industry were then combined. The dependencies between the groups were shown by using arrows. Finally, an overall answer to the question "What result would you like to get from the VariLight project" was created.

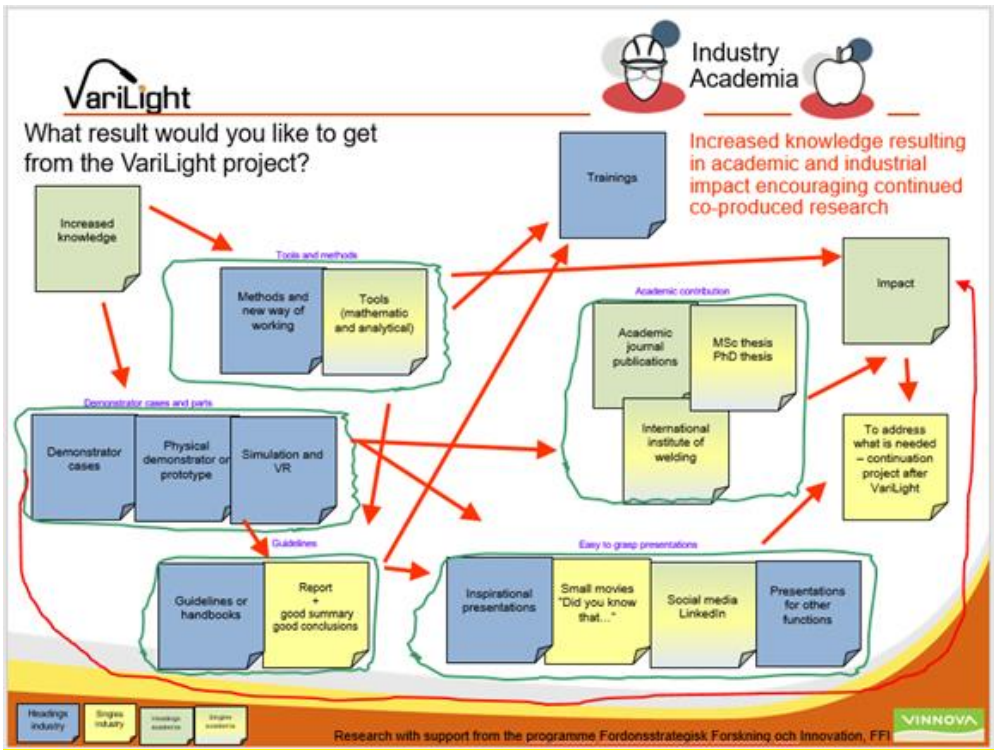

Figure 4: AIM workshop on desired project result.

The project regularly followed up the workshop that was done to synchronize industrial and academic expectations of results to ensure progress. As an example, the project decided to create a booklet with projects highlights as well as movies to address the requests from the industry.

6.2 WP2 Production

A master thesis work focused on understanding variation for different post weld treatment methods. HFMI is fastest, TIG gives best fatigue properties and burr grinding requires the least training.

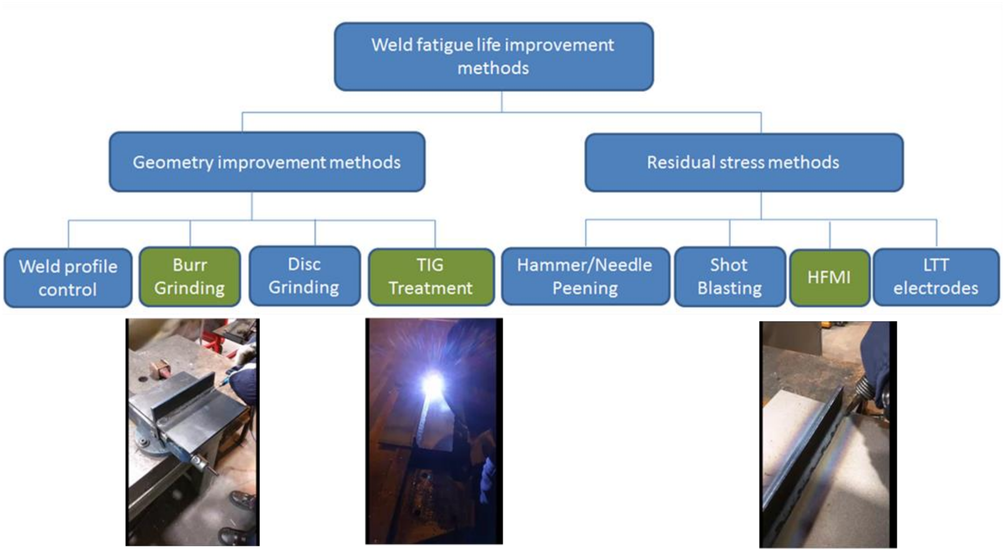

Figure 5: Study of post weld treatment variation.

Another master thesis work created a method to map, analyse and create a basis for decisions regarding variation in welding. A conclusion was that the result needs to be visualized differently depending on the need.

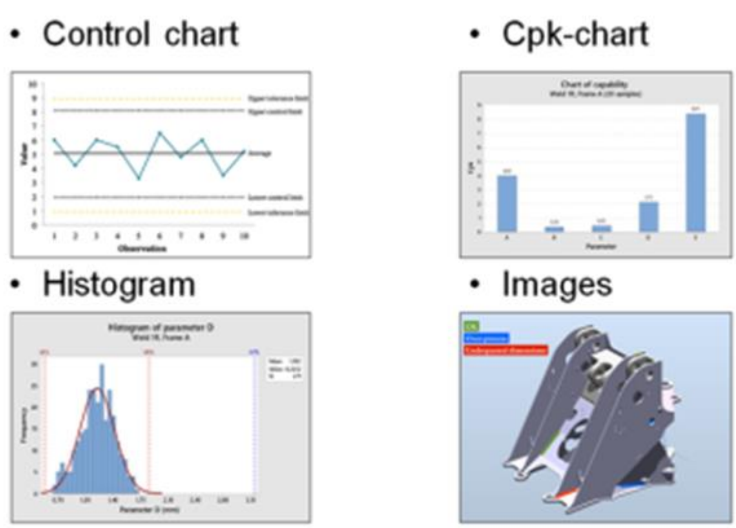

Figure 6: The measurement data needs to be presented in different ways depending on the usage.

An assessment of the production costs of fatigue-life-improved welded structures was done in an effort to quantify the efficiency of different fatigue-improving strategies. It was concluded that full life-cycle assessments are valuable policy and R&D support and enables strategic future investments on cost-efficient fatigue methods.

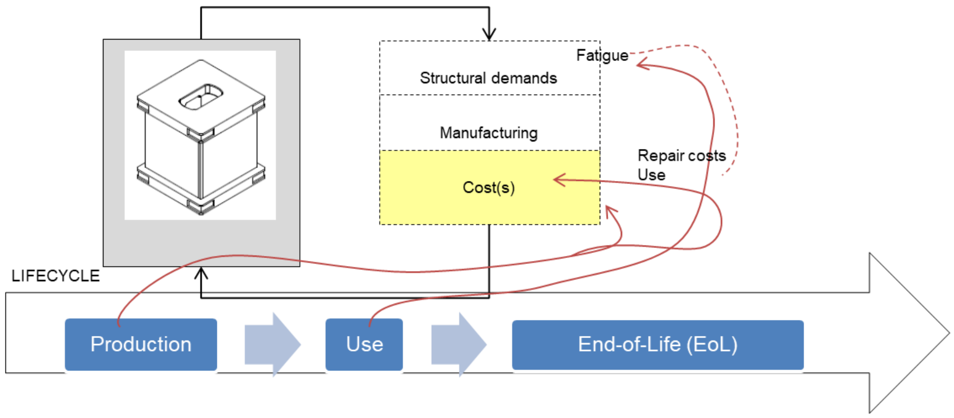

Figure 7: Full life-cycle assessments enables strategic future investments on cost-efficient fatigue methods.

A study was done to understand which quality measures to use with the introduction of quality control tools with much higher resolutions. The definitions of quality measures when applying new technology have a huge impact on how the technology succeed and if it is even possible to produce welds accordingly.
The new definitions should correlate to current quality levels and if wanted changes in quality levels are done should the allowable stress in design also be changed. By clarifying the quality definition as proposed by the study the number of deviations of a weld could be reduced by more than 90 %.

6.3 WP3 Cutting

The workpackage studied the standard for thermal cut edges and how the ordering process works as well as how the standards correlate to fatigue performance. Test pieces were cut using different methods at different suppliers. The test pieces were also measured using several methods before fatigue testing.

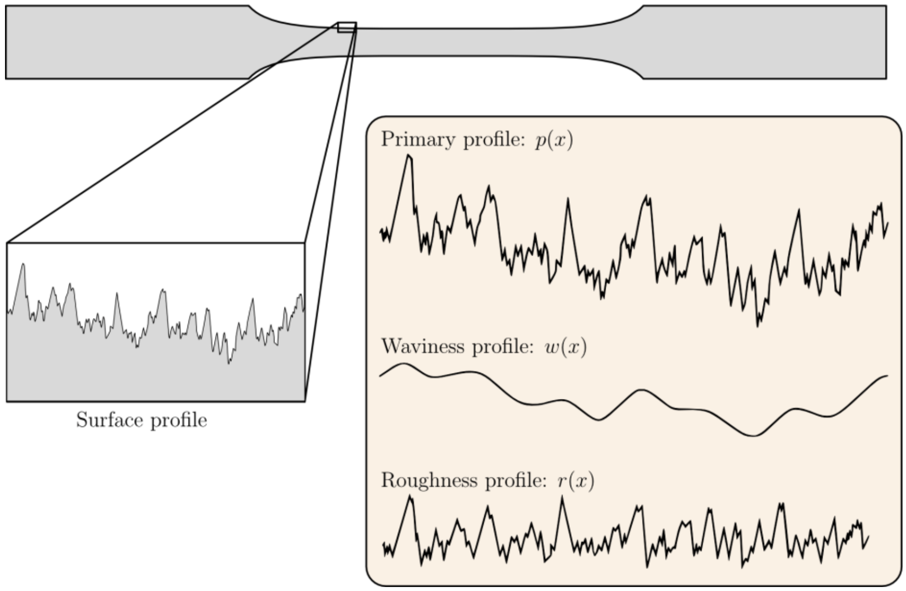

Figure 8: Measurement of cut samples.

6.4 WP4 Fatigue testing

A study to predict the fracture initiation location(s) based on the weld geometry was done as a thesis work. The plausible initiation location(s) could be determined for approximately 80 % of the fracture surfaces. Regression parameters could be fitted so that prediction of initiation location(s) had a hit rate above 90 % for this group of test specimens. In this study data from another research project has been used, FATSCAT.

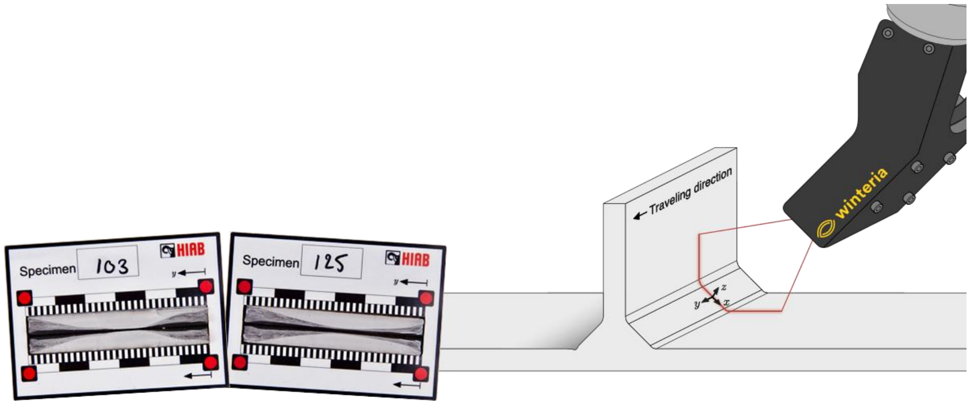

Figure 9:Predicting initiation location based on weld geometry.

A round robin (RR) project has been carried out where different organizations have calculated the life of a component that Bromma has developed. The results show that the local stress-based fatigue assessment approaches consistently give a better life estimation, and on the safe side, in comparison with nominal stress approach, when compared with the fatigue testing. The work has influenced other research constellations to perform similar round robins.

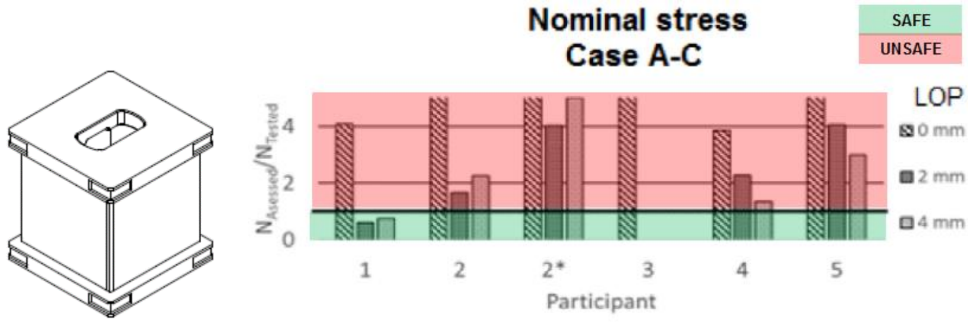

Figure 10: In the round robin (RR) project different organizations calculated the life of a box specimen.

In a thesis work the LEFM method has been employed to evaluate the fatigue life of the box-shaped welded structure. A parametric study was performed on various parameters such as lack of weld metal penetration, load position and plate thicknesses to investigate their effects on fatigue life. Compared to the other fatigue assessment methods such as nominal or notch effective stress method, LEFM can predict the residual life more accurately especially for intermediate LOP.

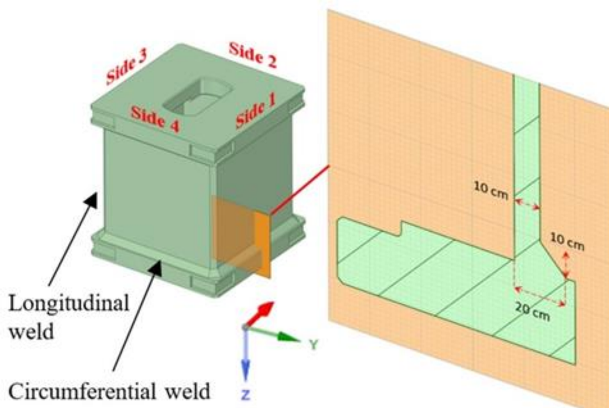

Figure 11: Evaluation of fatigue life of box specimen using LEFM.

An analytical probabilistic model for choosing welding parameters that satisfy a target requirement with a specified probability level, i.e. 90% reliability, was developed. The proposed probabilistic model yields process parameters set-ups that differs significantly compared with a traditional deterministic approach. It can be used to formulate guidelines for process parameters set-ups that satisfy a desired reliability level. The approach paves the way for optimization under uncertainty.

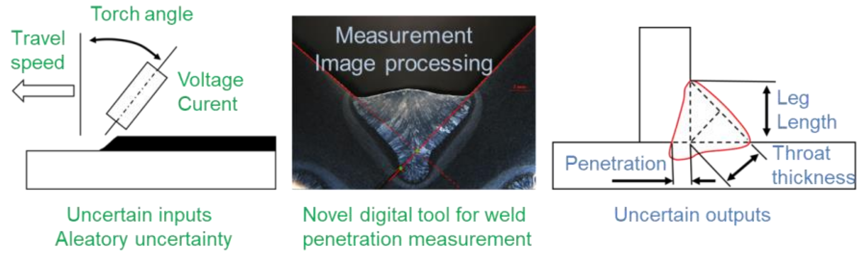

Figure 12:An analytical probabilistic model for choosing welding parameters.

6.5 WP5 Residual stresses

An investigation of the weld induced residual stress state in the box specimen was done using efficient computational weld mechanics concept. The prescribed temperature method can reduce the computational time by 80% as compared to the Thermo-elastic-plastic method. Furthermore, the computational time for using lumping method, together with prescribed temperature method is 65% less than the prescribed temperature method. However, the magnitude of residual stresses may be underestimated.

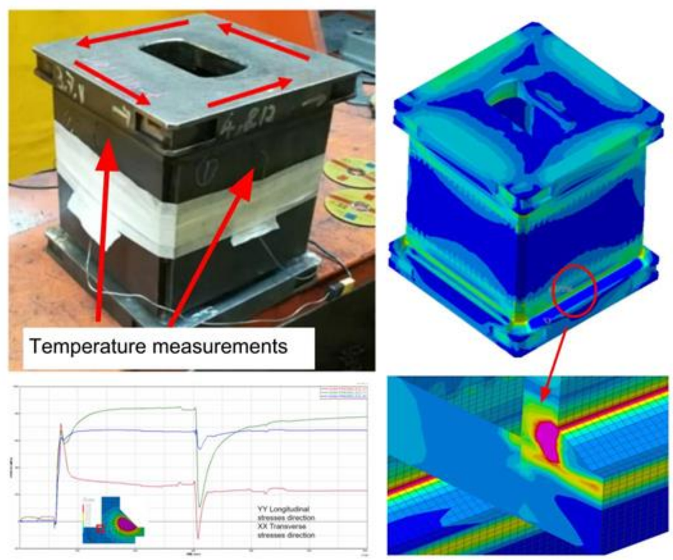

Figure 13: Weld induced residual stresses in welded structures using efficient computational weld mechanics concepts.

6.6 WP6 Load Analysis

The purpose of the study was to get familiar with big data analytics and to find a better prediction model for usage up to 10 years. On an individual level, crane usage can be extrapolated over the lifetime. The average accumulated stress history of the complete examined population is approximately linear. There is a need of better information about repaired/replaced components and product end of life.

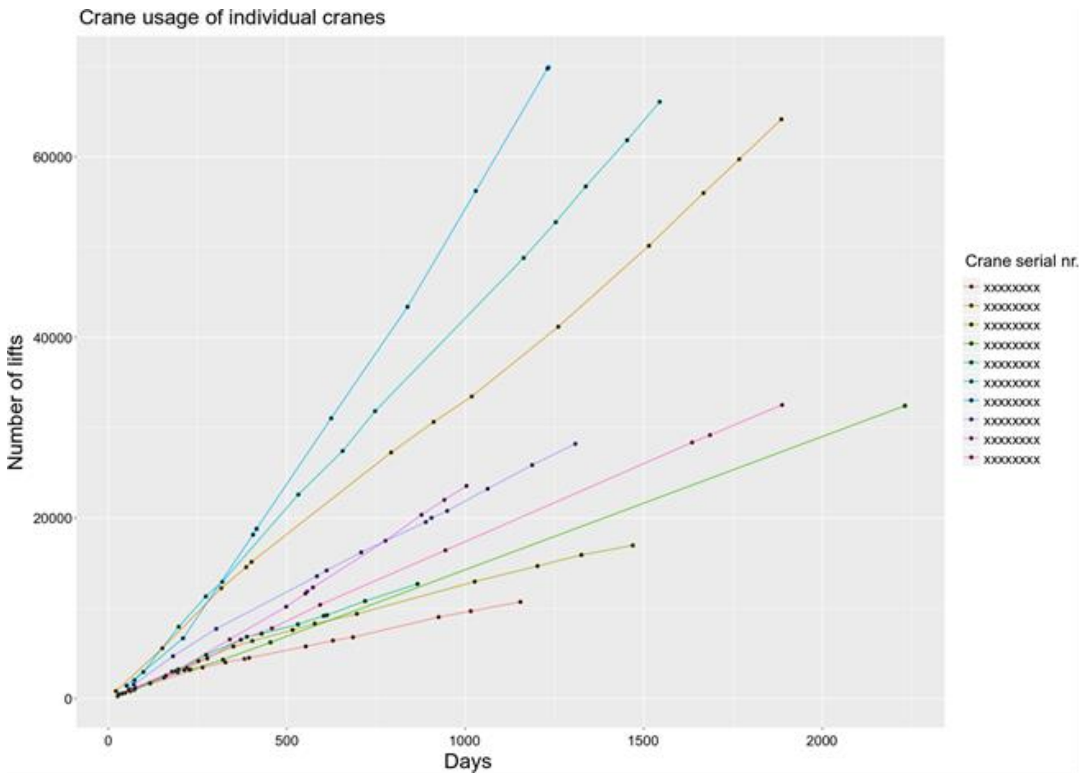

Figure 14: Crane usage can be extrapolated over the lifetime.

6.7 WP7 Ensemble of WP2-6

Robust engineering – understanding and mitigation the influence of variation – requires an elevated integrated system approach, since variation not necessarily depend on the same set of factors as the nominal value does. It needs to be focused on between-function-relationships and what information is needed to take relevant decisions in other functions - a system approach. An infrastructure for process feedback, in order to elevate data to information to knowledge to decisions for the right operational roles is necessary to build and maintain. Studies have shown the lack of standardized procedures for effective communication. This in order to define and set up precise data collection systems, define data handling, refining and visualization and process monitoring of the evolving experimental (testing of several conditions) and observational (monitoring of one condition) studies needed during the industrialisation phase when prototypes stepwise turn into serial production. The resolution of a measurement system needed for monitoring of one process condition over time is, for example, higher than the resolution required needed during testing in order to distinguish two or more conditions from each other. A conceptual complexity that in itself is a challenge to communicate across the organisation.

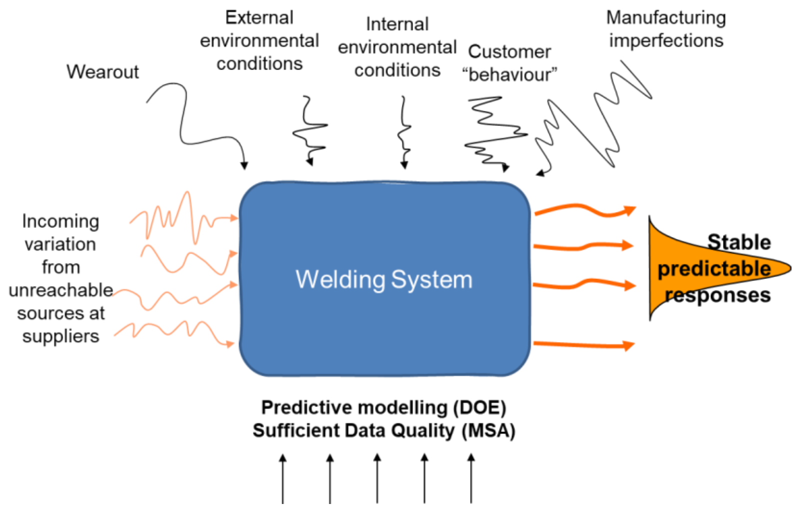

Figure 15: Control variation within the system, understand and mitigate incoming variation.

Holistic benefits:

- **Understanding variation**
  - Floating definitions of what and how to measure → unclear understanding of process capability → wrong specification → over processing
- **Mitigate variation**
  - New concept on elevated level in order to facilitate communication and joint understanding between functions and organizations, see Table 1.
  - Proactive control of welding based on predictive modelling
- **Eliminate variation**
  - Advancing modelling definitions for weld fatigue life estimations
  - Measurement system development – technology and procedures

Table 1: Different roles have different views that defines the hierarchy of variation in the welding fabrication

Level	Hierarchical level	Decision role	Why
--- Comparing manufacturing flows (productivity and planning issues) ---			
9	Variation between **factories**	Operations management	Investments and market strategy
8	Variation between **process design**	Factory management	Production strategy, quality, productivity, cost
7	Variation between **technology suppliers**	Production managers	Quality, productivity and cost
--- Comparing welds (capability issues) ---			
6	Variation between **batches & resetting**	Production planning, Purchase	Production sequence, SMED
5	Variation over time – **variation of the same weld between parts**	Line manager, Purchase	**VOP** PROCESS CAPABILITY (C_p, C_{pk})
4	Variation within **one part**	Production set-up	Variation between welds on the same part
--- Within ONE weld (design and welding technology issues) ---			
3	Variation along **one weld**	Welding engineer	Stability of the weld arc (WPS), welding technology and materials
2	Variation within **a cross section**	Design, FEM-calc & Welding engineer	WPS, welding geometry, load cases
1	**One weld toe**	Design, FEM-calc & joint testing	**VOC** - Calculation, stresses and life estimation

Lack of joint definitions of variations between engineering roles in different organizational functions prevents customer-based operational development of both welded structures quality and fabrication productivity. This has been investigated by three master thesis projects.

The designer easily becomes the decision bottleneck, entangled by tacit unmanaged feedback loops in the engineering information system. Decisions taken on unprecise data lead to larger margins and longer lead-times and over-allocated designers. Proposed injection: structural facilitation of the information system using swim lane mapping, as exemplified in the theses.

ANALYSIS DONE	INSTRUMENTS USED	CRUCIAL PEOPLE OUTSIDE	CAUSES OF PROBLEMS IN THE SYSTEM	EFFECTS CAUSED	ACTIONS TO TAKE
Qualitative analysis	Lean six sigma tools (swim lane and spaghetti diagram)	Top management that defining system roles	Wrong system understanding	- Bad allocation of resources - Lead-time increases	Catching the right involvement for each actor with, e.g. swim lane tool
Quantitative analysis	Bayesian network	Top management allocating of resources (budget)	Wrong understanding of root causes of critical failure	•Spending money on wrong activities •Over-production	• Advance skills in quality thinking • Advance data quality and data visualization • Cross-functional teams in all loops

Figure 16: Actions to improve information flow.

Understanding the communication issues affecting the variation level and mitigating the most significant ones with a standardized information flow is important. Visualization tools used in the Data analysis reports have an important impact on the discussion topics and level: it is possible to drive the discussion towards different subjects using different graphs and data visualization in order to facilitate inter-functional transfer of the right information.

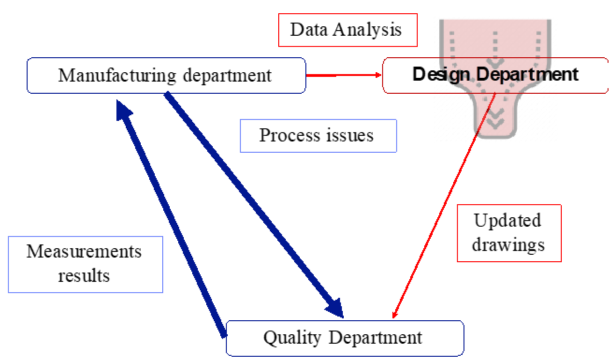

Figure 17: Information need for the critical roles.

The main contributions to the overall FFI targets can be summarized as:

- Increased research in areas of importance for the competiveness of Swedish vehicle industry, both at the universities and participating companies.
- Increased cooperation between the participating universities and industries with national and international connections
- Participation of a SME (Svetskommissionen) with an important role to disseminate the result to the Swedish industry

The project also contributes to a large extent to the targets of the Sustainable Production Technology programme:

- Reduced unnecessary safety margins in each step leads to increased productivity, reduced lead time, and decreased use of energy and material.

- The increased knowledge of the variation enables development of new products with reduced weight in load carrying structures. That means less material usage and increased handled ton/hour which gives lowered fuel consumption hence less environmental impact.
- Better and more reliable design procedures will reduce lead time in product development process.
- This will strengthen and further develop the competitiveness of the participating companies and the Swedish industry in regard to the manufacture of vehicle components and vehicles.

The project mainly contributes to the prioritized research areas within FFI sustainable production: Forming and joining, Geometry and quality assurance and Knowledge and technology distribution.

7. Dissemination and publications

7.1 Dissemination

There has been a focus during the entire project on different ways of spreading the project result. A significant amount of academic contribution has been done e.g. in the form of thesis work, journal papers and conference papers. The project has been very active in e.g. the Cluster Conference in Katrineholm and at IIW. The project will also have a final conference where the result will be presented. For the conference a lot of effort has been spent on making the content appealing to company representatives e.g. by having study visit, posters, mingle sessions and “meet a researcher”- sessions. The project has worked hard on creating ways of spreading the result also outside of the academic environment. That has been done e.g. through posters, short films and presentations at the companies. The project is now creating a booklet with project highlight to distribute at the conference as well to companies.

There have been collaborations with other researchers to gain the most of the result. For example, VariLight has been able to use data from FATSCAT and Quinman will use data from VariLight. Studies in VariLight has also influenced other research groups to conduct similar studies in other parts of the world.

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	x	Scientific papers in journals and conferences. Improved graduate courses at KTH and Chalmers in design and fabrication of welded structures Dissemination of results in IIW, national and international conferences and seminars.

Be passed on to other advanced technological development projects	x	Built on each other's results: Quinman and FATSCAT Projects within FFI: OnWeld Projects within SIP Lighter: INNODEFAB
Be passed on to product development projects	x	The results will be implemented in product development projects in production and design at the industrial project participants.
Introduced on the market	N/A	
Used in investigations / regulatory / licensing / political decisions	x	Update of corporate standards and recommendations for design and quality assurance at Volvo CE and SSAB

7.2 Publications

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6. Hultgren, Gustav. (2019) "Assessment of fatigue for laser-scanned weld surfaces: Correlation between weld geometry and fatigue initiation", KTH
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8. Conclusions and future research

The project has addressed the initial research questions. The project has increased the understanding of variation in each step of the process, from customer usage and design to manufacturing and testing. To create awareness is the first step towards doing the right actions to mitigate the effect of variation. The project has also taken a holistic view to help the organization to prioritize initiatives to gain the best overall effect.

As part of the result workshop, to identify further research was included in the project. The ideas will be included as part of the final conference and for example covers:

- Move from understanding outgoing variation to mitigating the influence of incoming variation
- Probability requirements.
- Product cost and LCC/LCA
- Influence of definitions/nomenclature.
- Changed quality assessment based on refined technologies or methodologies
- Analysis and visualization of data to hierarchy of variation.
- More accurate and reduced safety factors for local methods and to influence standards.

9. Participating parties and contact persons

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