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Nordic Innovation Centre

# Final report for: NI 00072

# GJUTDESIGN-2005

## Design, Kvalitet och NDT för gjutna utmattningsbelastade komponenter

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## Summary

Cast materials are widely used in drive trains, in cars, trucks, wind mills, ship engines, construction machinery and many other mechanical components. In 2000 a consortium of 21 industrial companies, universities and research institutes representing all Nordic countries initiated a joint research project with the goal developing improved methods and tools for fatigue design of cast structures and components. Consortium partners represent machinery, construction, manufacturing, energy production, ground transportation and shipping industries. The main objective of the initiative was to improve the reliability and reduce the time and effort required to design complex fatigue loaded cast structures by developing design guidelines, quality rules and cost-effective NDE systems. Work on the project has proceeded simultaneously along several fronts such as fatigue testing of small test pieces and real components, application of different NDE-systems, modelling and analysis of complex structures, and quantitative examination of factors influencing cast quality. All structures considered represent actual components from the participating industries. The analysis and testing include both multi-axial and linear elastic fracture mechanics (LEFM). During the project a broad analysis of the design process of cast components are started

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Project Time 2000 -2004

## Participants

There are 21 major participants in the project from Sweden, Finland, Denmark and Iceland. 15 companies, 4 university and 2 research organisations are among the active partners. In all 25 organisations has been involved in the project. 8 of the companies develop and manufacture fatigue loaded cast structures as construction machinery, trucks, windmills, paper rolls, robots, cranes and large ship engines, 5 are foundries companies and 1 are consultancy, se Table 1.

Table 1.

| **Company/Institution** | **Company/Institution** |
|---|---|
| (Volvo CE) Volvo Articulated Haulers Volvo Construction Equipment Components, Volvo Wheel Loaders. | CHL (Chalmers Lindholmen)<br>CTH (Chalmers University) |
| Volvo Truck , Volvo Buss | KTH (Dep of Aeronautical and Vehicle Engineering |
| ABB Research, ABB Robotics | Metso Papers, Metso Drives |
| DNV (Det Norske Veritas) | Componenta OY, Componenta Pistons |
| Arvika Gjuteri | Wärtsilä Technology |
| KEYCAST | VTT (Technical Research Center of Finland) |
| Svenska Gjuteriföreningen | LUT (Lappeenranta University of Technology) |
| Alfgam Optimering AB | Valdemar Birn AS |
| FOI (Försvarets Forsknings Institut) | ICETEC |

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**Steering group chairman:** Prof. Anders Blom FOI
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## Technical results

**Introduction C**ast materials are widely used in drive trains and in structures of cars, trucks, wind mills, ship engines, construction machinery and many other mechanical components. . The main reasons for the use of castings are the possibility to achieve an "optimal" geometry and good machining properties.

Cast aluminium is used in transmission cases and engine blocks for cars. Grey iron is used in engine blocks in heavy vehicles and ship engines. Nodular cast iron is used in axle cases, transmission cases, hubs, attachments and linkages in as well trucks as construction machinery and in hubs of windmills. Cast steel is used in the welded structures of construction machinery and also in some offshore platforms. All these components and structures are required to sustain fatigue loading and the number of significant load cycles can be significant varying from $10^{7-}10^{9}$ during their economical life of the structure.

A general problem with casting is the existence of defects. The fatigue strength of "defect free" materials is governed by ultimate strength, surface finish and residual stress levels and there is proportionality between fatigue strength and ultimate strength for polished specimens. With increasing surface roughness, the proportionality between fatigue and ultimate strength is lost and for rough surfaces, the roughness rather than the material strength controls fatigue. At this stage the life is mainly dominating by crack propagation and the fatigue strength is inverse proportional to the defect size (crack, roughness depth, and inclusions a. o.). The size and location of different type of defects govern the fatigue strength of the actual component and it is important to reduce or remove defects or remove "defect" components from production lines.

For cast materials there is a number of different quality standards, 9 different external standards were identified in a 1997 Volvo CE-project dealing with acceptance criteria. All these standards have a systematic error in common, the absences of a connection between acceptance limits and fatigue design strength.

Existing NDT-technology require time, knowledge and investments regardless type of material. Simple, fast and cost effective systems are not in general use or exist in the market causing difficulties in serial production of fatigue sensitive components to guarantee a certain level of defects in cast materials. Detailed strength and fatigue analysis is the slowest link in the chain leading from new design concept to realisation. For critical fatigue loaded components, target failure rates are in the range 1x10-4 during their economical life. Lack of precision in the fatigue analysis can raise this figure by one or two decades.

In 2000 a consortium of 21 industrial companies, universities and research institutes representing all Nordic countries initiated a joint research project with the goal developing improved methods and tools for fatigue design of cast structures and components Consortium partners represent machinery, construction, manufacturing, energy production, ground transportation and shipping industries. The main objective of the initiative was to improve the reliability and reduce the time and effort required to design complex fatigue loaded cast structures by developing design guidelines, quality rules and cost-effective NDE systems.

Work on the project has proceeded simultaneously along several fronts such as fatigue testing of small test pieces and real components, application of different NDE-systems, modelling and analysis of complex structures, and quantitative examination of factors influencing cast quality. All structures considered represent actual components from the participating industries. The analysis and testing include both multi-axial and linear elastic fracture mechanics (LEFM).

In some cases alternate life prediction strategies are used and, when possible, compared to measured fatigue lives. During dynamic testing of structures attention was given to the location and orientation of fatigue damage in addition to the number of load cycles to failure.

**Fatigue analysis methods.** For cast materials there are three main methods available for fatigue analysis, the SN-approach which is based on fatigue testing of smalls scale specimens or components, the local stress strain method which is based on fatigue testing of small scale specimen in displacement control and finally LEFM based on fatigue test of cracked specimen. In multi-axial situations the complexity increases and these methods needs modifications and introduction of equivalent measures or analysis in different planes in the structure.

The majority of mechanical industries, except the aeronautical and nuclear industries, are working with the SN-approach. Since the fatigue strength is related to both defect size and defect location in the component, the scatter can be extremely large. The scatter is also emphasized by the blasting operation, which cast components are subject to as part of the cleaning operation. The blasting is, in most cases of intensity greater than in shot peening and causes compressive residual stresses on the cast surface.

The local stress strain method rely on more or less defect free material and should be used only on cast components which undergo 100 % NDE or other means to guarantee the quality. The availability of relatively cheap software on the market is a risk for miss-use of the method.

Linear elastic fracture mechanics, LEFM, is an accepted and established way to predict fatigue failure due to propagating cracks. It is widely used within the aeronautical, space and nuclear industry. Yet, there are difficulties regarding the incorporation of LEFM in order to estimate length of life for specific components. The application of LEFM in mechanical industry such as car, truck and construction machinery industry are limited and often only connected to failure investigations. One reason for the limited use of LEFM is that the area is new and the education at university level started just 30 years ago. Another reason is that it is still a very time consuming exercise to handle crack growth in complex geometry. The problems with complex boundary conditions, large models and concentrated loads, should not be underestimated. A third reason is the lack of research in crack growth of cast materials in comparison to steel, titanium and aluminium. The lack of research may be a result of lack of demand from the sectors using cast materials.

One major problem in connection with nodular cast iron is the scatter in LEFM-material data. For mild and medium strength rolled steel there is a general consensus about LEFM data and they are also introduced in international design guidelines as IIW (1). For nodular cast iron the scatter in terms of slope and position of the LEFM-data is large in the literature.

**Defects.** Microstructures that develop during solidification of a ductile iron casting are to a great extent influenced by the specific foundry process. The casting itself affects the solidification by its thickness and complexity. Properties of a casting in ductile iron can however never be characterised by the microstructure alone when a cast component never can be delivered free from defects. There are always isolated micro shrinkages in the vicinity and in hotspots and dross defects near surfaces. An investigation conducted at Volvo[1] show that leading foundries in Europe always deliver cast components with dross defects close to the surface every now and then. Therefore a perfect microstructure must be defined as a microstructure that contains small isolated defects i.e. micro shrinkages. The only thing the foundry can granite is small volumes that are free from defects. These volumes must be located close the critical section where the stresses are at maximum and where a fatigue crack is likely to initiate. The foundry must find a way to design the ingate-system and feeders in a way that the critical volumes are free from defects and all defects are located in areas that has a low load. A practical tool here is filling and solidification simulation of the casting. As a cast component becomes more optimised with thin walls the significant of the defects increase. The obvious question is how serious the defect is and how large it can bee. In an earlier project[2] investigations on specimens taken from real cast components and from rig tested components under spectrum loads showed that a Kitagawa plot was a practical tool to predict in a defect of a certain size could imitate a fatigue crack. Here the conclusion was that defects as small as 0,3-0,4 mm in maximum dimension can cause initiation of a fatigue crack. This corresponds to a stress intensity range (ΔK) of 4 $MPa\sqrt{m}$ . In a more practical situation, estimated from a rig test on real components under spectrum load a stress intensity (ΔK) of 10 $MPa\sqrt{m}$ is more realistic. This means in practical terms that a defects with maximum length of 0,5 mm subjected to a load (Δσ) of 100 MPa must bee considered as a potent danger. In the literature[3] it is also possible to determine the risk different types of defects put on the stressed component. Dross defects are for instant more dangerous than shrinkages.

**NDE.** To perform non destructive testing (NDT) on cast material there is some key properties of the test object that has to be taken under consideration. These are mainly surface roughness, varying thickness and high acoustic damping. The NDT methods can be divided into two categories, surface- and volumetric methods. Since the main objective (in this specific NDT situation) has been to detect subsurface defects in steel castings, no surface NDT method has been under consideration. The two major volumetric methods are ultrasonic and radiographic testing. Due to the properties of the grain structure of cast material tends to introduce grain scattering and thus also difficulties in penetration.

For high reliability components, reliable NDE will increasingly become part of the manufacturing quality inspection process. Implementation of NDE systems for many mechanical engineering components remains a relatively expensive process. Normally it is limited to ultra high reliability systems like aerospace or nuclear installations where high costs can be justified or to ultra-high volume production where dedicated systems can be used. Flexible systems that can be used inexpensively for numerous components each with yearly production runs of several hundred or several thousand units are not available.

**Design Process**. Design and manufacturing of complex mechanical structures for use in transport equipment, vehicles and similar will require that attention be given to a number of critical issues. The competing demands associated with lead-time, cost, quality and fuel consumption need to be set against those of durability and structural integrity. For cast structures this is a difficult process including many different steps and the lead-time and performance rely on success in all steps. The function and the assembly of the structure affect the basic geometry and the stress distributions control the local geometries. Since fatigue life is a results of different combinations of stress levels, residual stresses and defects (in a fatigue loaded structure), simultaneous engineering together with manufacturing is required.

There is a need to develop a robust design process for cast components were the major requirements must be assessed as early and correct as possible. Such process needs guidelines, simulation tools, robust fatigue assessment methods, and quality systems. To achieve adequate quality in serial production there is a need to improve weld quality system and base it on a more scientific ground and automate NDE at reasonable cost.

## Outline of the work.

The project has been conducted in Sweden and Finland within 4 main areas. A number of investigations within different aspects of cast material in fatigue loaded components. The topics studied can be grouped under defect development, defect detection (NDE), critical fatigue issues and design process for cast material

## Results and discussion

**Defect Development.** In this project another type of foundry defect is investigated, chunky graphite. Chunky graphite is a form of degenerate graphite, which often develops in the final regions to solidification in heavy castings[4]. Of special interest in this project is the influence of silicon as the newly developed ductile iron, ISO GJS-500-10 has a silicon level of 3,7 %. Components cast in this alloy sometimes show a slight tendency to form chunky graphite. The graphite degeneration can significantly reduce the mechanical properties of the casting, especially fracture toughness and other measures of ductility. This is especially dangerous for components exposed to fatigue loads. The threshold is more or less unaffected but in combination with the lowered fracture toughness can cause a lowered lifetime for the component. According to the literature the foundry must concentrate on accomplish as short solidification time as possible and as high nodular cont as possible in hot spots of the component. These actions will reduce the segregation of the chemical elements, especially the tramp elements of the melt. The project initiated a deeper study in this area. A PhD student is now working with the assignment to verify the findings the literature survey found. This study is financed outside this project

**NDE.** Surface ultrasound examination and real-time X-ray systems have been investigated as part of this project. Technically the systems are promising, but rapid processing of the vast amount of data that is produced remains a challenge. Flexibility of the systems must also improve.

Tests were carried out with a high-resolution x-ray system (HiReX). It consists of an imaging device, 450 kV x-ray machine and a manipulator. The imaging device is a 12 bit, cooled CCD. The CCD is coupled, without magnification, to an input screen made of scintillating fibres. It is optimized for best possible performance for crack detection in 20-60 mm thick steel components. In terms of x-ray energy it is equivalent to 250-450 kV. The high radiographic sensitivity enables detection of defects less than 1 percentage of the object thickness (e.g. pores less than 300 μm in diameter are visible in objects of 30 mm in thickness).

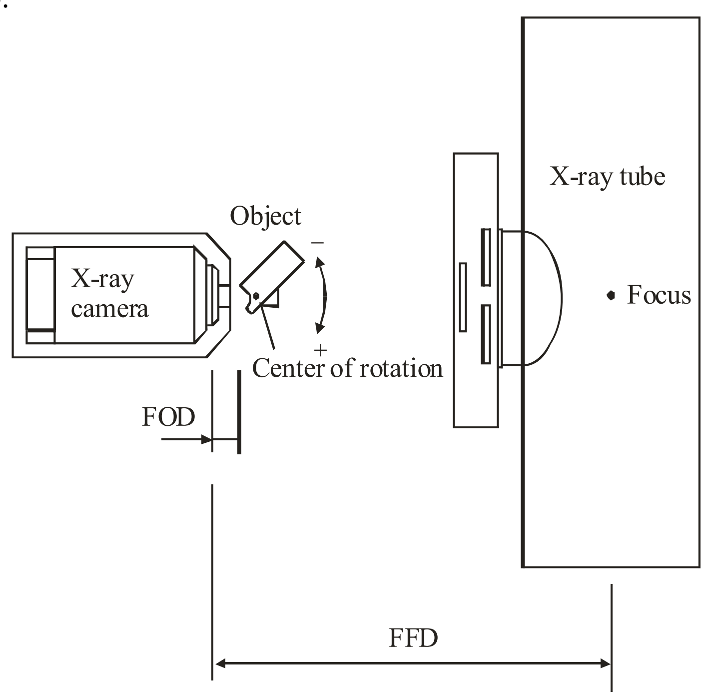


**Figure 1. The HiReX-system and test object.**

To be able to use the 12-bits dynamics of the X-ray camera and also to separate the defects from the surface roughness, two different techniques has been developed. An image enhancement method has been developed to compensate for curved surfaces. The CCD-camera within the system generates 12 bits of information but the human eye can only separate less than 128 grey-levels, which corresponds to 7 bits of information. Defect information can saturate in grey-levels caused by large variation in thickness or attenuation coefficients in the object. The defect information can though be retrieved by alteration of contrast and brightness but is a time consuming procedure. These iron cast objects often tend to be of complex geometries, which have enforced the development of a filtering technique that withdraws the geometrical information from the radiograph. The developed filtering technique has been proven to enhance the detection of defects in objects with geometrical variations and has a potential to reduce time-consuming analysis of radiographs. The difference in grey-levels in figure 2 between a slag indication (in the upper half) and a wolfram inclusion is more than 700 levels which makes them impossible to visualize in the same picture. After the image enhancement they are though clearly both visible (the right one).

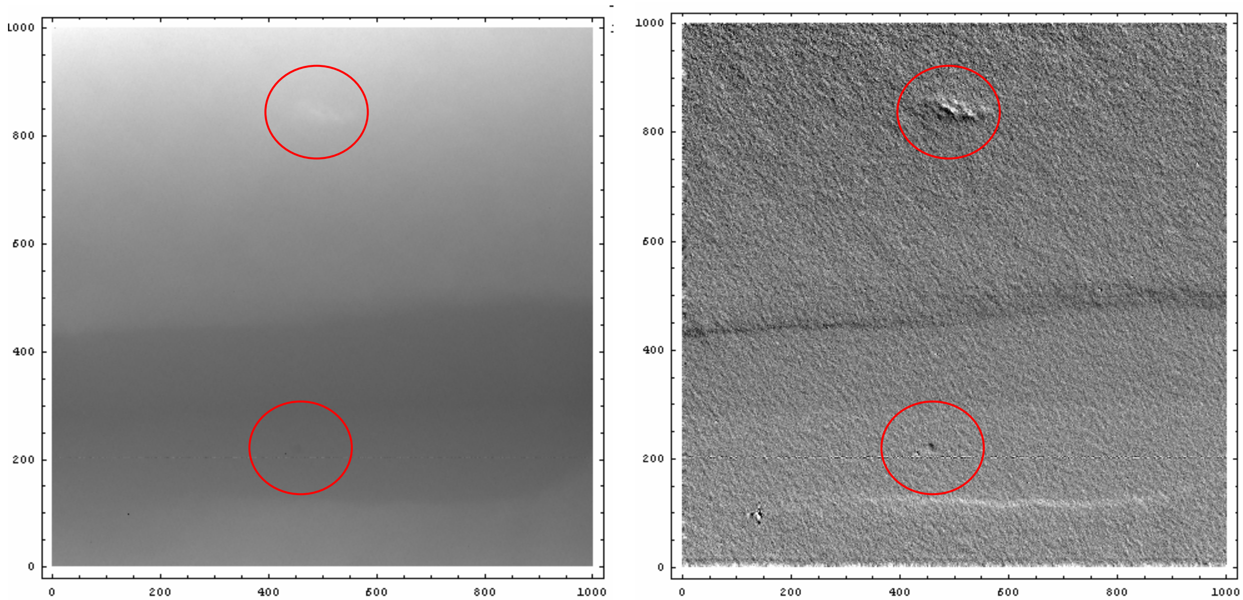

**Figure 2. The digital radiograph (left) and corresponding after using modified wavelet filtering.**

The other developed technique is to separate the subsurface defects from effects of the surface roughness, by adding a series of exposures together into a short video animation. A series of exposures where taken with increments of 1°. Each image where then compensated for local variations in thickness. The animation is produced in conventional AVI-file format. The subsurface defects where then visible in the animations.

**Critical Fatigue Issues.** Nodular cast iron. The fatigue test of small scale specimen with and without chunky graphite show that the da/dN curve is not affected to any extent by the chunky graphite, but the fracture toughness is reduced in same order of magnitude as the elongation.

The fatigue strength of machine components that are subject nominally to constant amplitude load can be drastically reduced by only a few rare r under-load events. These events are in many cases part of the normal duty cycle and are the result of thermal transients during start-ups and shut-downs or due to maintenance. Critical experimental measurements of this overload effect have been made for grey and nodular iron and for QT steel.

For complex parts, loading is often multi-axial and in some cases is also highly non-proportional. Fatigue damage models have primarily been developed for materials that fail predominantly by shear crack growth. Cast materials, however, fail predominantly by tensile mode crack growth. There is a need to develop models for this class of material and verify the results for large and often complex components.

**Design Process** For cast load-carrying and work producing components and structures there is a need to integrate efficient FE based analysis tools, reliable information on defect size, shape and location, and expertise on how complex variable amplitude and multi-axial loading influence fatigue damage in cast materials. In terms of assessing the significance of defects in different regions of a component, fracture mechanics methods are a valuable too, but are not often applied to cast components. Reliability of these methods, especially in regards to material parameters, is needed and has been a valuable contribution of this project.

To get a simple tool for the designers and to make the communication easier between the buyer and the deliverer of castings a special standard (10) has been developed. The standard classifies and defines different type of defects in ductile iron seen from size, number and location. Further on demands are given when the component can be accepted after correcting measures.

## Conclusions.

In order to gain a competitive advantage in the world marketplace, Nordic industries need to press forward in several critical research areas. For cast load-carrying and work producing components and structures there is a need to integrate efficient FE based analysis tools, reliable information on defect size, shape and location, and expertise on how complex variable amplitude and multi-axial loading influence fatigue damage in cast materials. Important steps have been made in order to better implement fracture mechanics based fatigue assessment procedures for cast materials. Progress has been made in cast process modeling and control to avoid major defects and avoidance of chunky graphite that is often associated with high silicon iron. Several potential tools for reliable NDE have been investigated.

# References

1. Hobbacher, A, Fatigue Design of Welded Joints and Components, Recommendations of IIW, XIII-1539/XV-8454-96, Abington Publishing 1996
2. L-E. Björkegren, Slutrapport, Vamp-7, Dimensionering av gjutna komponenter med avseende på defekter, korta ledtider och lättviktskonstruktion, 1999.
3. Robertsson, Defect Sensitivity in Nodular Cast Iron for Safety Critical Components, 1993, Volvo internal report LM-500245
4. Einarsson, M. Sinander, S. Smedendahl, Defect Sensivity in Cast Materials, 2002, Examensarbete vid Chalmers Lindholmen, Institutionen för Maskinteknik, Rapport Mi3-40-2002
5. Swedish Standard SS-EN 1563
6. Björkblad A, Conventional vs. closure free crack growth in nodular iron, To be published at the 15th European Conference of Fracture (ECF 2004), August 2004, Stockholm, Sweden.
7. M. Mörtsell, K. Hamberg, J Wasén, Crack Initiation in Ductile Cast Irons, In Proc. 7.th. Int. Conf of Cast materials, Barcelona, 2002
8. K. Ham berg, L-E Björkegren, Chunky Graphite a literature survey, Report 300930 at the Swedish Foundry Association
9. Björkblad, On the prediction of crack propagation in cast steel specimens, 9th Portuguese Conference of Fracture, Setûbal, 2004, pp. 167-175.
10. K. Hamberg and S-E Stenfor, " Defekter i järngjutgods, ett förslag till ny standard**".** Gjuteriet, Nr 3, 2002, pp10-15
11. L-E Björkegren and K. Hamberg: "Lätta segjärnskonstuktioner genom optimering av materialegenskaper och konstruktiv utformning". Svenska Gjuteriföreningensskrift 970930
12. H. Kaufmann, "Zur schwingfesten Bemessung dickwandiger Bauteile aus GGG-40 unter Berücksichtigung giesstechnisch bedingter Gefügeganzen", LBF Bericht Nr. FB-214, 1998
13. K. Hamberg, L.E. Björkegren and Z.X. Sun "Chunky Graphite in Ductile Iron, a literature survey.", Gjuteriföreningspublikation, 2003
14. B. R. Rabb, "Influence of occasional underloads on fatigue," European Congress on Computational Methods in Applied Science and Engineering, ECCOMAS 2004, 24-28.7.2004, Jyväskylä.
15. Marquis, G. B., Rabb, B. R., and Karjalainen-Roikonen, P., "High Cycle Variable Amplitude Fatigue of a Nodular Cast Iron," J. of ASTM International , ASTM International, West Conshohocken, PA, 2004.
16. Marquis, G. and Karjalainen-Roikonen, P., Long-Life Multiaxial Fatigue of a Nodular Cast Iron, In: ESIS Special Technical Publication on biaxial/multiaxial fatigue and fracture, A. Carpentieri, M. de Freitas, and A. Spagnoli (eds.). 2003.
17. Marquis G. Fatigue assessment and future trends in multiaxial fatigue, 7th Intl Conf. Biaxial and Multiaxial Fatigue and Fracture, 28.6-1.7.2004, DVM Publishers, Berlin, 12 p.
18. Marquis, G. and Murakami, Y., Scatter in the Fatigue Limit of Nodular Iron, Materials Science Research International, Special Technical Publication, Kyoto, Japan, 2001, T. Hoshide (ed.), pp. 92-96
19. H. Wirdelius and Lars Hammar, Modeling of a high resolution digital radiographic system and development of a filtering technique based on wavelet transforms , NDT & E International, 37:1 (2004), pp 73-81.

20. L. Hammar and H. Wirdelius, HiReX- development of a high resolution digital X-ray system , Proc. 16th WCNDT, Montreal (2004).
21. L. Hammar, Inspection of steel casting fatigue specimens with High Resolution Digital X-ray (HiReX) , Comm. SCeNDT-0401, Göteborg (2004).
22. B. Israelsson, Kvalitetsstyrning vid framställning av stålgjutgods – En genomgång av processen vid svenska gjuterier, Gjuteriföringsskrift 040913, 2004
23. S, Bahta, Analysis of Impact of Weld Repair on Complex Steel Castings, Examenensarbete Volvo CE