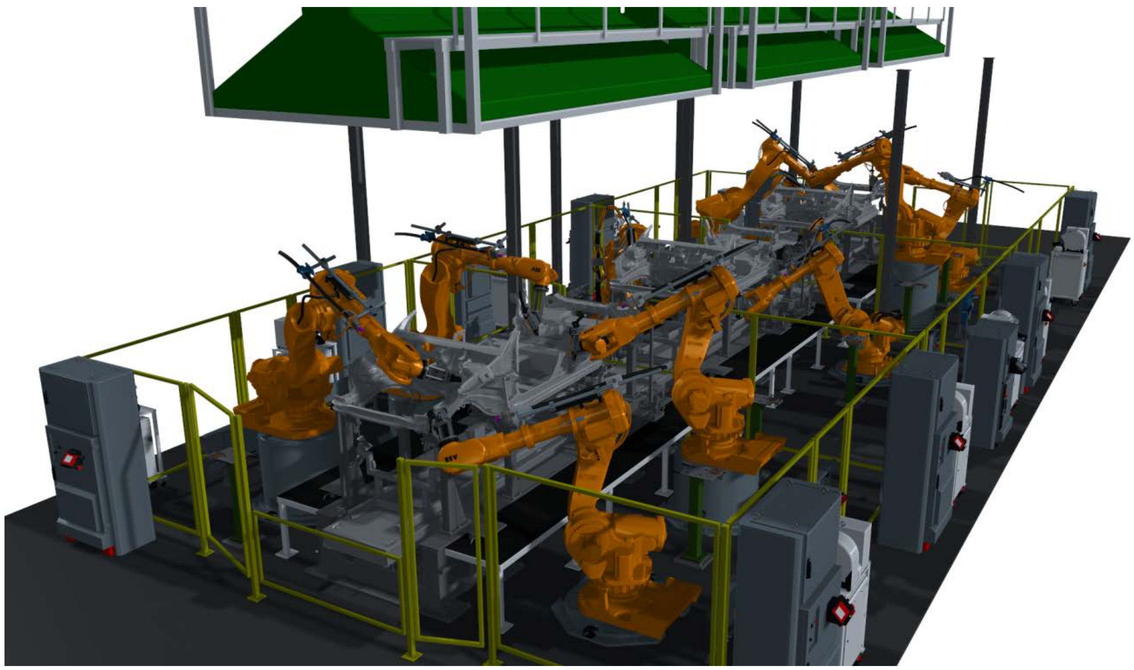
Automatic Path Planning and Line Balancing



Project within FFI-Sustainable Production Technology

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Content

there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**
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1. Executive summary

Today, the margins of automotive manufacturers are moderate and competition is fierce. The industry furthermore faces shifts of paradigms regarding propulsion as well as styling, with environmental requirements ever-present. Effective product realization response is thus important. Today, although most development is done virtually, design decisions are still based on experience rather than mathematical analysis. This project targets the car body, which has a significant influence on safety, aesthetics, handling, fuel economy and top speed.

A typical car body consists of sheet metal parts joined by about 4000 welds, distributed in assembly plants with hundreds of welding robots, organized in up to 100 stations. Therefore the equipment needs to be utilized to its full potential. The balancing of weld work load has a significant influence on the production rate and equipment utilization. However, weld load balancing is still manually conducted, due to the lack of proper methods and tools. Therefore, this work aims at developing automatic methods to maximize equipment utilization and dimensional quality over an entire production line.

The overall objective of the project is a more cost-effective manufacturing engineering work, by math based methods and tools. In particular, the goal is efficient production equipment utilization and efficient and effective geometry simulation. This enables frontloading of manufacturing requirements on product development as well as increased insensitivity to late changes.

The main goals are

- A productivity increase of 25% in detailed process design,
- A productivity increase of 25% in sheet metal assembly stations.

The strategy to reach the objectives is (i) to treat station design parameters together, based on a chronological framework for virtual sheet metal assembly design. (ii) to utilize and further develop automatic path planning combined with discrete optimization techniques in order to automatically load balance, sequence and find collision free motions and (iii) to continuously implement the results in the IPS software demonstrator, since this way of working has proven to guarantee the usefulness of the project results, (iv) to use real industrial case studies to quantify the level of success in reaching the objectives.

The project has been carried out in 6 work packages

- WP1: Line balancing and station design for throughput and quality,
- WP2: Path planning and discrete optimization,
- WP3: Path Planning of Robot with Cables,
- WP4: Advanced Geometrical Surface Analysis,
- WP5: Demonstrator and Dissemination of Results,
- WP6: Project Management,

and has benefited from a joint effort with the research activities of FCC and Volvo Cars in the Wingquist Laboratory VINN Excellence Centre for Virtual Product Realization.

A world first automatic method for load balancing of welds in robot lines has been developed and implemented in the IPS software tool. The method (i) has been successfully applied in vehicle programs, (ii) will be rolled out to all vehicle programs and body shops at Volvo Cars, and (iii) is described in 5 principle scientific publications. Furthermore, the project has resulted in a PhD thesis in product and production development at Chalmers, and the project won the VOLVO CARS TECHNOLOGY AWARD 2011 in the category "Research".

Application of this method shows 25% better equipment utilization, and 75% reduction of offline programming- and commissioning-costs. The method enables concurrent manufacturing engineering and product development, increases insensitivity to late changes, and provides backup solutions for robot break downs.

The project won the VOLVO CARS TECHNOLOGY AWARD 2011 in the category "Research".

2. Background

Automobiles are an integral part of modern society and its way of life. In addition, automotive manufacturers are important institutions in society, summing the work of a vast array of sub suppliers, employing many. The margins are however moderate and competition is fierce. The automotive industry furthermore faces shifts of paradigms regarding propulsion as well as styling. Fundamental technical innovations, primarily to meet environmental requirements, that are moreover not a trivial issue to foresee, will affect all parts of the operation. It is thus important that product realization can respond quickly and effectively to market impulses using no more resources than necessary. Today most aspects of development are conducted in a virtual environment. However, design decisions are still based on experience rather than mathematical analysis. This project targets the car body, or the Body-in-White, BiW, which is perhaps the most defining part of any car, with a significant influence on safety, aesthetics, handling, fuel economy and top speed.

A typical automotive car body consists of about 300 sheet metal parts, joined by about 4000 welds. Typical joining methods are spot welding, arc welding, gluing and stud welding. In car body assembly plants, the welds are distributed to several hundred industrial welding robots, which are organized in up to 100 stations. Sheet metal assembly is indeed an investment intense type of assembly. Therefore the expensive equipment needs to be utilized to its full potential. The balancing of weld work load between the executing stations and robots has a significant influence on achievable production rate and equipment utilization. Robot line balancing is a complex problem, where a number of welding robots in a number of stations are available to execute an overall weld load. Each weld is to be assigned to a specific station and robot, such that the line cycle time is minimized. Line balancing efficiency depends on station load balancing, robot welding sequencing, path planning and effectiveness of robot coordination for collision free execution within each other's working envelopes. Robot coordination impairs cycle time by inserting waiting positions and signals into the original paths.

However, there exists no automatic simulation based method for weld load balancing over entire production lines. Furthermore, in industrial practice, weld load balancing is still manually conducted, based on experience and time consuming trial-and-error analysis in CAE-tools (Computer Aided Engineering). Therefore this work aims at developing automatic simulation based methods for weld load balancing over entire production lines to maximize equipment utilization as well as dimensional quality. Since the criterion of dimensional quality is coupled to cycle time and thus to equipment utilization, it is added as a second criterion in this project.

3. Objective

The objective of the project is a more cost-effective manufacturing engineering work, by math based methods and tools. In particular, the goal is efficient production equipment utilization and efficient and effective geometry simulation. This enables frontloading of manufacturing requirements on product development as well as increased insensitivity to late changes.

The main goals are

- A productivity increase of 25% in detailed process design,
- A productivity increase of 25% in sheet metal assembly stations.

4. Project realization

The strategy to reach the objectives is (i) to treat identified station design parameters together, with respect to equipment utilization and geometrical quality, based on a chronological framework for virtual sheet metal assembly design. (ii) to utilize and further develop automatic path planning combined with discrete optimization techniques in order to automatically load balance, sequence and find collision free motions and (iii) to continuously implemented the results in the IPS software demonstrator available for the project partners, since this way of working has proven to guarantee the usefulness of the project results both during and after the project, (iv) to use real industrial case studies to quantify the level of success in reaching the objectives.

The project has been carried out in 6 work packages

- WP1: Line balancing and station design for throughput and quality,
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In more detail,

4.1 WP1: Line balancing and station design for throughput and quality

This work package has mainly been conducted as an industrial PhD Project. Participants are: Johan Segeborn, VCC (PhD Student), Anders Carlsson, VCC (Industrial Supervisor), Johan S. Carlson, FCC (Assistant Academic Supervisor), and Rikard Söderberg, Chalmers (Academic Supervisor). The PhD student is member of the research team at the academic partner FCC.

The research is driven by answering the question: How can Automatic Path Planning & Line Balancing, integrated with Dimensional Variation Analysis, make sheet metal assembly more cost-effective?

1. How can design parameters be optimized with respect to the criteria of assembly equipment utilization and geometrical assembly variation?
2. Which information flows can enable such a process?
3. How can analytical and automatic tools be utilized and further developed in order to enable such a process?

4.2 WP2: Path planning and discrete optimization

When deciding how to perform a spot or stud welding operation in a line of multi-robot stations there exist many possible alternatives since the operation can be done by more than one robot and with many welding gun configurations. Furthermore, if several robots share the same workspace then their motions need to be coordinated in order to guarantee that no collision can occur. In this WP the focus has been to develop and implement mathematical algorithms within collision free path planning and discrete combinatorial optimization. In particular, the deliverables includes, new smoothing algorithm for robotic motions, improvements and generalisation of the load balancing algorithm and a strategy for simultaneously balance between interlocking losses and sequence losses to optimize the final cycle time.

4.3 WP3: Path Planning of Robot with Cables

Many industrial robots are dressed with cables and hoses feeding the tool with signals, current, pressurized air, water cooling, fastener, paint and sealing material. etc. These hoses and cables have serious impact on the allowed robot configurations and motions in a robot station. The reason is the risk of breakage due to high stresses and wear, which has a direct impact on availability. In this WP the focus has been to use the recent progress in real time simulation of cables and make extensions to enable simulating a real dress pack and robot retractor system. Validation of different simulation approaches with reality has been carried out. This WP is important to prepare for an integration of cable simulation in the load balancing algorithms.

4.4 WP4: Advanced Geometrical Surface Analysis

The position of tasks like studs, spot welds, and inspection features is driven by functional and esthetical requirements such as safety, strength and quality, but also by factory attributes such as equipment utilization and throughput. However, before these factory attributes are optimized by feasibility, reach ability, path planning and load balancing there is today a time consuming step of manual work. This step is to ensure that the task positions are robust considering the geometrical properties of surfaces. The main challenge is to find algorithms that are insensitive to shortcomings of the surface. These shortcomings can depend on either human errors or the triangulation algorithms in the CAD system. Therefore, in this work package the focus has been to explore using the graphical card and image analysis to automatically identify and quantify the interesting geometrical surface properties that ensure robust task positions.

5. Results and deliverables

A world first automatic method for load balancing of welds in robot lines has been developed and implemented in the IPS software tool. The method (i) has been successfully applied in vehicle programs, (ii) will be rolled out to all vehicle programs and body shops at Volvo Cars, and (iii) is described in 5 principle scientific publications. The project has also resulted in a PhD thesis in product and production development at Chalmers.

Application of this method shows

- 25% better equipment utilization, and
- 75% reduction of offline programming- and commissioning-costs.

And the method enables

- Concurrent manufacturing engineering and product development,
- Increased insensitivity to late changes,
- Backup solutions for robot break downs.

The project won the VOLVO CARS TECHNOLOGY AWARD 2011 in the category "Research". "Research": Favors innovative research / development work that has demonstrated the potential for providing a competitive advantage or a significant technological enhancement. Research category nominations can also include pure science or breakthrough discovery achievements with limited implementation opportunities but provides future long-term advancement potential.

The developed and implemented algorithms on path planning and line balancing have been successfully tested on a 3 station stud weld line with 10 robots and a 2 station line with 8 robots at Volvo Cars. The number of studs is about 200 in each line. A comparison between the cycle time for the running production programs optimized by an experienced robot programmer and IPS generated programs has been carried out. The comparison, including interlocking losses between robots, has been carried out in VCC:s OLP software Process Simulate. The results for Stud line 1 and Stud line 2 are presented below showing an improvement of 23% and 54% in cycle time.

Industrial Reference Line							
		Running Production			Automatic Method		
station	robot	# welds	Robot CT	Station CT	# welds	Robot CT	Station CT
st1	r11	17	45.1	73.8	20	55.1	57.7
	r12	19	56.2		21	57.3	
	r13	20	73.8		20	57.7	
	r14	20	60.9		20	57.3	
st2	r21	22	53.4	55.5	21	54.3	54.3
	r22	23	55.5		20	53.5	
st3	r31	18	50.7	**80.5**	20	58.2	**61.9**
	r32	18	51.3		21	61.5	
	r33	16	48.5		19	61.9	
	r34	28	80.5		19	55.4	

Industrial Reference Line II							
		Running Production			Automatic Method		
station	robot	# welds	Robot CT	Station CT	# welds	Robot CT	Station CT
st1	r11	24	66.7	113.7	24	73.0	**78.8**
	r12	30	113.7		25	78.5	
	r13	20	74.5		25	71.0	
	r14	20	61.9		26	78.8	
st3	r31	26	105.1	**121.4**	25	70.6	72.0
	r32	29	121.4		26	72.0	
	r33	24	74.2		25	69.8	
	r34	28	80.2		25	68.8	

Related detailed technical result high lights from the project are:

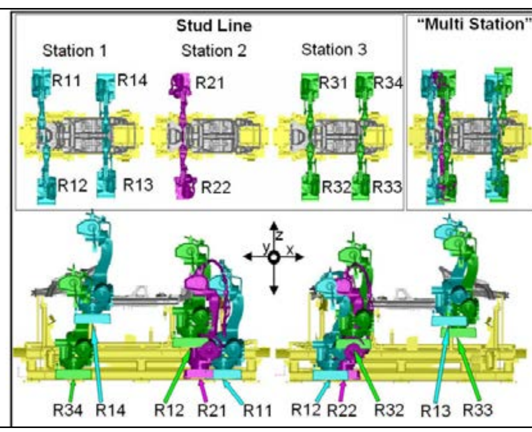
- An algorithm for generalized line balancing considering cycle time and spatial separation of welds has been developed. The method is expected to scale well to large lines since it can use different levels of estimated robot travelling costs, and hence trading speed for accuracy.
- A genetic algorithm that optimizes welding sequences to minimize assembly variation has been developed and implemented. The algorithm has been successfully applied on industrial cases.
- A genetic algorithm for weld sequence optimization of dimensional variation and cycle time has been implemented based on IPS and RD&T.
- A method and algorithm that resolves interlocking conflicts between robots by load balancing, sequencing, task configuration and coordination. The algorithm is

part of the line balancing algorithm that gives the results presented in the Section Goal. The result proves that conflicts can be removed with small loss in cycle time,

- A new approach for treating sequencing and interlocking in parallel based on generalized TSP has now been tested with promising results for up to 4 robots and 40 welds. The algorithm can resolve tricky geometrical interaction problems between robots making it also suitable for geometry stations. The work will be submitted for publication as “A Decoupled Approach for Collision-Free Routing and Scheduling in Multi-Robot Stations”,
- A new load balancing algorithms based on a direct inter and intra robot edge swapping technique has been implemented.
- A smoothing algorithm for robotic motions that allows for better control between clearance and short paths demands,
- Conducting a cable and DressPack simulation of an ABB IRB6640 in IPS. The task was to simulate a flexible tube component while enabling full contact handling with cables and robot links,
- Compared simulation with reality to get a better understanding of cable behaviours in virtual and real environment,
- An automatic method for determining robustness welding positions based on computer graphics and image analysis.

5.1 Method Automatic Path Planning and Line Balancing

In this Section we describe how the main algorithms and software is applied to achieve the overall goal of maximising equipment utilization by the math based CAE demonstrator of the project.

<table>
<tr>
<td>Create a multi station by superimposition of the scenes and geometries of the line stations, with maintained robot positioning relative to the product (car body).</td>
<td>


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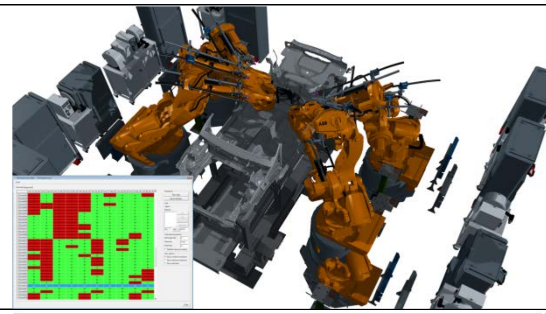
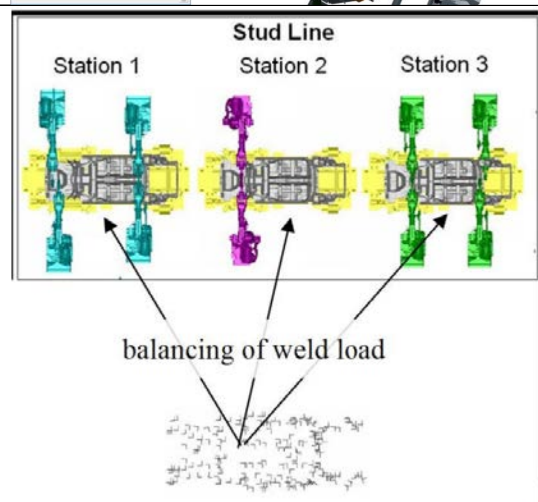
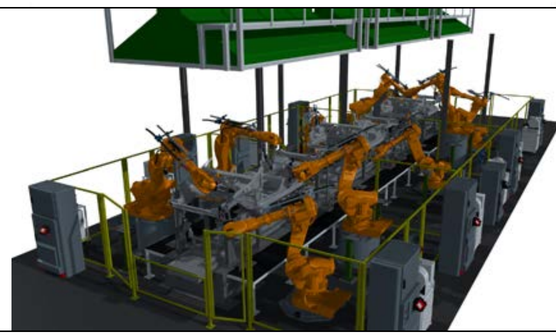
Task Plan to find collision-free alternatives to perform each welding operation in the multi station.	
Distribute the welding operations between the stations and robots to minimize estimated cycle time and with preference to robot weld separation within and between the stations.	
Minimize cycle time by integrating balancing, sequencing, path planning and coordinating on the welds distributed to each Station in the previous step.	

5.2 Delivery to FFI-goals

- The project has developed methods, algorithms and software tool that enable a productivity increase of 25% in detailed process design and a productivity increase of 25% in sheet metal assembly stations, by fast and accurate consequence- and optimization studies.
- The project results contributes to environmental targets by enabling a fast and responsive product realization that can meet new environmental requirements, which technical solutions will not be trivial to foresee, by a significantly increased level of automation in virtual production process development.

- Furthermore, the methods and tools of the project aim at reducing material usage and increases equipment life length. In this way the results directly supports Sustainable Vehicle and Power train Production by minimizing physical efforts and reducing the resources needed to produce each items.
- The project results can also be used for designing a sustainable production system by flexible sheet metal assembly station and line design, where equipment can be effectively reused.
- The project results significantly reduce factory equipment costs, which is the main cost in automated sheet metal assembly plants. Furthermore, it significantly speeds up the product realization development process. In this way, the project contributes towards a vehicle industry in Sweden that continues to be competitive.
- The math based approach in this project is a key to meet the challenge of increased complexity in detailed process design due to the increased number of product variants when combined conventional power and new environmental power trains are mixed.
- Increases the use and the understanding of advanced mathematics in production development.
- Increases the corporation between industry, university and research institutes.
- The project has resulted in an industrial PhD at Volvo Cars in cost effective virtual sheet metal assembly design.
- The project has further strengthened Sweden’s competitiveness as advanced user and developer of digital tools methods in the border line of product and production.
- The research group of Geometry and Motions Planning at FCC which is part of the environment for innovation and collaboration; Wingquist excellence centre at Chalmers for efficient product realization, have been further strengthened growing from 9 (2009) to 14 researchers.
- The software platform IPS for math based virtual product realization has been further developed and will continue to secure comprehensive and fast implementation of research results, as well as facilitates technology exchange between the industrial partners.

6. Dissemination and publications

6.1 Knowledge and results dissemination

Increased interest in automation for small series production, shorter development time, more product variants in the same line and better use of resources are driver of changes. All this changes are directly supported by the project results. During 2012, Volvo Cars will invest in the method, technology and software to take full advantage of the project results. AB Volvo aims at setting up a pilot study for a detailed evaluation of the project results in their environment for virtual process preparation and planning.

The collaboration on virtual product realization with Wingquist Laboratory at Chalmers and its VINNEX Centre will continue. This is an excellent platform for further disseminations, both in industry and academia.

The project results and demonstrator has continuously been disseminated during company visits and seminars, e.g.

- Wingquist Laboratory International Seminar, Göteborg, December, 2009.
- Production Engineering Research at Scania Södertälje, April 2010.
- NordDesign 2010 Conference, Göteborg, Sweden, August, 2010.
- ASME 2010 International Mechanical Engineering Congress & Exposition, Vancouver, British Columbia, Canada, November 12-18, 2010.
- Wingquist Laboratory International Seminar, Göteborg, December, 2010.
- Manufuture Conference, Wingquist Laboratory, Göteborg, December, 2010.
- The Annual Volvo Cars PhD Conference, Göteborg, 2010.
- Volvo Cars Manufacturing Research & Advanced Engineering Seminar, February 2011.
- Mötesplats för framtidens framgångsrika verkstäder, Katrineholm, May 2011
- Workshop at BMW "Virtual Improvements BiW", Munich, March 2011
- ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE2011, Washington, DC, USA, August 29-31, 2011.
- ASME 2011 International Mechanical Engineering Congress & Exposition, IMECE2011, Denver, Colorado, USA, November 11-17, 2011.
- Wingquist Laboratory International Seminar, Göteborg, December, 2011

6.2 Publications

1. Eek, G., Eriksson C, "Effective methods for solving the balanced and synchronized multiple TSP using genetic algorithms", Master thesis, University of Gothenburg, supervisor Ekstedt F., examiner Wahde M., June 2009.
2. Segeborn, J., "Towards an Effective Virtual Sheet Metal Assembly Development Process Securing Geometrical Quality and Equipment Utilization", Licentiate Thesis Chalmers University of Technology, 2009.
3. Omicevic, A, Elbing, R., "Simulering av Bultsvetsrobotar med IPS 2.0", Bachelor thesis Högskolan Väst, Juni 2010.
4. Spensieri, D., Bohlin, R., Ekstedt, F., Torstensson, J., Carlson, J., S.,"Throughput Maximization by Balancing, Sequencing and Coordinating Motions of Operations in Multi-Robot Stations", In Proceedings of the NordDesign 2010 Conference, August 25 – 27, 2010, Göteborg, Sweden.
5. Segeborn, J., Segerdahl, D., Carlson, J. S., Carlsson, A., Söderberg, R., "Load Balancing of Welds in Multi Station Sheet Metal Assembly Lines," In Proceedings of the ASME 2010 International Mechanical Engineering

Congress & Exposition, Vancouver, British Columbia, Canada, November 12-18, 2010.

6. Segeborn, J., Wärmefjord K., Carlson, J. S., and Söderberg, R. “Evaluating Genetic Algorithms on Welding Sequence Optimization with Respect to Dimensional Variation and Cycle Time” In Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE2011, Washington, DC, USA, August 29-31, 2011.
7. Segeborn, J., Segerdahl, D., Ekstedt F., Carlson, J. S., Carlsson, A., Söderberg, R., “A Generalized Method for Weld Load Balancing in Multi Station Sheet Metal Assembly Lines” In Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition, IMECE2011, Denver, Colorado, USA, November 11-17, 2011.
8. Segeborn, J., “Cost-effective Sheet Metal Assembly by Automatic Path Planning and Line Balancing, Integrated with Dimensional Variation Analysis”, PhD Thesis Chalmers University of Technology, 2011.
9. Segeborn, J., Segerdahl, D., Ekstedt F., Carlson, J. S., Andersson, M., Carlsson, A., Söderberg, R., “An Industrially Validated Method for Weld Load Balancing in Multi Station Sheet Metal Assembly Lines” Submitted to The Journal of Manufacturing Science and Engineering, American Society of Mechanical Engineers, ASME, 2011.

7. Conclusions and future research

This project presents a world first automatic simulation based sheet metal assembly line balancing method, which significantly increases assembly equipment utilization. All of the line balancing design parameters are jointly treated by the method. Applied on a stud welding line of 3 stations, 10 robots and about 200 stud welds, the method produces a line cycle time significantly better than that of the corresponding running production programs. The time required for line balancing is reduced from several months to about one day. The method is implemented in the CAE-tool IPS and is thus ready for broad based industrial application. This project furthermore increases knowledge regarding the trade-off between assembly equipment utilization and geometrical assembly variation, and how the two criteria can be jointly treated, in particular with respect to welding sequences. Geometrical simulation of complex robot cables during motions including self contact has been validated in collaboration with ABB.

In future research the influence of the spatial positioning of industrial robots could be added to the line balancing method. Moreover, the method could be integrated with some modular fixture design. This could further speed up detailed process design, and increase the level of design automation. Since this work supports sustainable production by minimizing resources needed to assemble the Body in White, it could be further enhanced by also relating the results to energy savings. Furthermore, the cable simulation technology should be included in the line balancing method to avoid early breakage of robot dresspack, this should preferable be done in close collaboration with e.g. ABB. However, robot down time in the factory is unavoidable and there is a great need to create back up programs allowing for the line to continue producing with reduced speed instead of a total stop.

An industrial and research challenge is to generalize the results to be applicable for complex geometry stations, which may feature several plant assembly steps, where robots need to be synchronized to secure a multi robot welding sequence. Among other thing this means that geometrical assembly variation needs to be added as a second criterion, to the line balancing method.

8. Participating parties and contact person

This has been a collaboration project with the industrial partners Volvo Car Corporation, SAAB Automobile, Volvo AB, Scania CV and the research partner Fraunhofer-Chalmers Research Centre (FCC). A steering group with one representative from each partner has been appointed for the management of the project. It has been responsible for the project control, economy and reporting to VINNOVA. The daily operations of project management have been handled by Magnus Jivefors, Volvo Car Corporation (Industrial project leader) and Johan S. Carlson, FCC (Academic project leader).

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